

REFINING THE SPAN AND RATES OF DEPOSITION OF THE GLENWOOD PHASE OF  
LAKE CHICAGO

BY

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THESIS

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## **Abstract**

The Glenwood Phase of proglacial Lake Chicago is its oldest phase, but is the least studied. Previous studies concentrated on the two more recent phases: The Calumet and Nipissing. As a result, there is significantly more concrete data concerning the history and supporting the ages of the latter two phases, but little for their predecessor. For example, prior to my study there was only one radiocarbon date accepted as representing Glenwood Phase sediment that had an error of less than 500 years. In addition to the lack of knowledge regarding the age of the Glenwood phase, the mechanics of the transition between the Glenwood and Calumet phases is currently debated.

By executing my research plan, and using previous concepts and age models of Bretz, Hansel, Mickelson, Thompson, Kehew and others, I have redefined the span and age of the Glenwood Phase to 16,800-15,100 cal yr BP, a hiatus of high-level lake sedimentation from 15,100 to 14,010 cal yr BP, followed by a transgression to the Calumet level. Identification of a intra Glenwood/Calumet low is new and difficult to reconcile with available chronology of linked systems. My analyses were completed by analyzing DEMs based on LiDAR data, obtaining sediment cores of Glenwood Phase sediment, selecting plant macrofossils from the cores, and interpreting ages and age models of the 22 radiocarbon age determined by accelerator mass spectrometry (AMS). Supporting data are grain size and clay mineral analyses

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# INTRODUCTION

In this study, I will explore the relationship between the last deglaciation of the Laurentide Ice Sheet and the Gulf of Mexico, focusing on the early history of Lake Chicago discharge via the Chicago outlet and rivers draining to the Gulf of Mexico. In the southern Lake Michigan basin, ancient maximum levels for Lake Chicago and Michigan are approximated by the altitude of beach ridges and spit ridges representing the Glenwood, Calumet and Tolleston levels (Leverett, 1897; Table 1).

**Table 1:** Summary of previously estimated ages and elevations above sea level for each lake phase that resulted in outflow via the Chicago Outlet. Lake Michigan has a current elevation of 176 meters

	Lake Chicago				Lake Michigan	
	Glenwood level (ASL)	Glenwood Phase	Calumet level (ASL)	Calumet Phase	Tolleston level(ASL)	Tolleston Phase
Leverett and Taylor, 1915	195 m	n/a	187 m	n/a	181 m	n/a
Bretz, 1951	195 m	n/a	189 m	n/a	183 m	n/a
Hansel and Mickelson, 1988	195 m	14.1-12.7 ka	189 m	11.5-11 ka	184 m	5-4 ka
Chrzatowski & Thompson, 1992	195 m	14.5-12.2 ka	189 m	11.8-11.2 ka	184 m	4.5-4.0 ka

The Glenwood and Calumet Phases occurred during the late Pleistocene, whereas the Tolleston is of Holocene age. Although significantly modified by post-settlement activities and structures, digital elevation model (DEM) maps using recent LiDAR data provide accurate landform altitude values in many places. Levels of ancient lakes are usually approximations because littoral landforms are not developed or formed by processes acting at mean lake level. For example, the mean lake level was interpreted to be lower than the altitude of Calumet and Nipissing beach ridges, and yet lake levels are reported higher than Glenwood spit ridges (Figure

1; Chrastowski and Thompson, Figure 2) and this relationship is shown in Figure 1. The discrepancy is because beach ridges are wave-built, and are roughly three meters higher in elevation than mean lake level. Wide beach ridges, such as the Calumet beach (Figure 2), are often festooned with dunes as high as 3 m (Figure 5). Spit ridges, on the other hand, are formed by longshore currents, and lake levels are assumed to be about 2 to 3 m higher than the landform (Figure 5). These discrepancies explain why maximum landform altitudes do not necessarily match mean lake level estimates.

The mechanism of how lake levels dropped following these highstands is debated (Hansel and Mickelson, 1988; Chrastowski and Thompson 1992; Kehew, 1993), and the precise water plane altitudes may only be approximated to within about two meters (Thompson, 1989; Chrastowski and Thompson, 1992). High resolution chronologies of protected bays, lagoons, and lakes adjacent to Lake Chicago could assist in interpreting the mechanisms of lake level declines. Though there are many radiocarbon dates accepted for delimiting the age of the Calumet Phase (Schneider and Hansel, 1990), prior to my study there were six ages attributed to the Glenwood, and each age had high errors ( $>500$  years) except for one:  $16,800 \pm 270$  cal yr BP (Table 2, Appendix B). Until this study, organic material associated with the Glenwood Phase had not been dated using accelerator mass spectrometry (AMS) methods. AMS dating is preferred to conventional radiocarbon dating as it assays significantly smaller samples, i.e. about 20 milligrams compared to 10 grams of wood, charcoal or needles for a finite age of about 15,000 cal yr BP. Small, relatively delicate samples (e.g. needles) are likely to provide better age estimate of lake levels than large, bulky wood samples since the latter material can better withstand weathering in surficial soil horizons and possible reworking and redeposition into lakes and streams. The errors calculated from the dates in this study are significantly smaller than

previous data (i.e. 35-110 years compared to ~500). This study will tie my revised and expanded history of the Glenwood Phase with downstream records of cut-and-fill sediment records in the middle Illinois River Valley (Hajic et al., 2006; Curry et al., 2015), alluviation in the lower Mississippi River Valley (Rittenour, 2005), and records of meltwater contribution to the Gulf of Mexico observed in the Orca Basin (Aharon, 2003, Williams et al., 2010;), located on the northern slope of the Gulf of Mexico (Figure 3). My results will be useful for holistic models of long-term earth surface processes such as ocean level, salinity, and temperature response to deglaciation (e.g. Tarasov and Peltier, 1995).

Sedimentary systems related to my study are located between the Gulf of Mexico and the Laurentide Ice Sheet. The relationship between meltwater floods of the Laurentide Ice Sheet and sedimentation in the Gulf of Mexico has been explored through stable oxygen isotope ratios ( $\delta^{18}\text{O}$ ) of foraminifera tests, clay mineralogy, and hydrologic modeling. Theoretically, a meltwater “signature” from the Laurentide Ice Sheet would include sediment entrained from the glacial source as well as sediment eroded along the river valley terraces. Not only would there be a mineralogical signature (Sionneau et al., 2010), but a “meltwater signature” of  $\delta^{18}\text{O}$  recorded in foraminifera tests (Flower and Kennett, 1990; Aharon, 2003). There are multiple sediment records for interpreting the effects of meltwater inputs to the Gulf. Many records, are located in the deepest part of the Orca Basin (e.g. Flower and Kennett, 1990; Flower, 2011; Williams et al., 2010); many consider this location ideal because the records are more likely to be conformable. These records highlight the largest floods, such as the Meltwater Pulse 1a (MWP-1a) of the Bølling-Allerød Phase. Aharon’s (2003) record is also from the Orca Basin, but from the

northern slope, where the record is more sensitive to archiving flood events not present in the other records, and more useful for my study.

Braid belts in the lower Mississippi River valley record episodes of high discharge and aggradation (Rittenour, 2005). One belt, the Kennett surface, dating from approximately 16.1 ka to 14.4 ka, likely correlates with discharge of Lake Chicago during the Glenwood Phase.

North of the Mississippi River valley, the next up-gradient location with meltwater records of the Laurentide Ice Sheet that drained via the Chicago outlet are deposits in the middle of the Illinois River Valley. The valley fill was characterized prior to modern lowland flooding that established the Emiquon National Wildlife Refuge near Havana, Illinois, (40.33°N, -90.10°W; Hajic et al., 2006; Curry et al., 2014). The successions indicate multiple large floods that eroded channels, some through 50 meters of alluvium and lake sediment to bedrock, including the Kankakee Torrent ( $18,930 \pm 50$  cal yr BP), an unnamed event at about 15,700 cal yr BP, and the youngest flood to erode to bedrock just prior to  $15,170 \pm 55$  cal yr BP (Figure 4). At Emiquon, channels eroded by large floods migrated from west to east, resulting in a complex of nested channels (Curry et al., 2014). The youngest large flood was followed by slackwater conditions that persisted in the Illinois River Valley until about 13,000 cal yr BP.

The Deer Plain (Savanna) Terrace, located in the lower Illinois River Valley, is a key landform that provides a temporal and geographical link between Lake Chicago and the Gulf of Mexico (Hajic, 1990). The terrace may be considered a delta that prograded towards Lake Chicago in response to floods and aggradation of the flood plain of the Mississippi River valley and lower Illinois River valley. The terrace acted as a dam for slackwater Lake Calhoun that occupied the middle Illinois River valley from about 15,700 to 13,040 cal yr BP (Hajic, 1990). Lake Calhoun existed during parts of the Glenwood and Calumet Phases of Lake Chicago and



was temporarily drained as the valley was eroded by large floods at about 15,700, and 15,200 cal yr BP (Curry et al., 2014). Additionally, Curry et al. (2014) state “the maximum possible lake depth at ca 15,800 cal yr BP at Emiquon was about 18 m, and by 13,000 cal yr BP was less than about 1 m.” Hence, the history of sedimentation in the middle Illinois River valley was controlled largely by the sediment supply from overflow of the Chicago outlet on the north, and northward progradation of the deltaic Savanna-Deerfield terrace due to flooding in the Mississippi River valley.

The Glenwood, Calumet and Tolleston shore complexes encompass distinct high stands of late Pleistocene Lake Chicago and Holocene Lake Michigan (Figure 2). The timing of their formation is vital to understanding of the complex history of Lake Chicago and Lake Michigan, but the processes which established stable lake levels capable of forming spits and beaches are disputed. The “classic” lake levels (meaning the elevation above sea level that is attributed to an individual phase of Lake Chicago) and their general ages have been consistently reported in the literature (Leverett and Taylor, 1915; Bretz, 1951; Hansel and Mickelson, 1988; and Chrzatowski and Thompson, 1992; Table 1). However, the mechanisms that drove changing lake levels remain debated: Bretz (1951) hypothesized that the drop of Lake Chicago from the Glenwood to the Calumet phases “resulted from the episodic down-cutting of the glacial outlet”. Following Bretz, Kehew (1993) suggested that these episodes were a result of sporadic and catastrophic meltwater discharge to Lake Chicago from Glacial Lake Saginaw via the Grand Valley in Michigan. Hansel and Mickelson (1988) posited that the drop in lake level was controlled by loss of contributions of meltwater from basins adjacent to the Lake Michigan basin due to outlets opening to the north and east (Figure 5). When the Grand Valley was open, the water flowing through the Chicago outlet included meltwater from the Michigan, Huron and Erie

lake basins. When the Grand Valley closed due to advance of the Saginaw or Lake Michigan lobes, the water that reached the Chicago outlet was only from the Lake Michigan Basin. As support for their theory, they cited new radiocarbon ages, not available to Bretz, which suggested the Chicago outlet was eroded to its current bedrock channel during or prior to the Glenwood Phase ( $14,760 \pm 460$  cal yr BP and  $15240 \pm 460$  cal yr BP, Table 2, Appendix B). Both theories acknowledged that the maximum altitude of Lake Chicago was controlled by the Chicago outlet. In sum, the Bretz school contended that downcutting was abrupt and caused by catastrophic or large floods; Hansel and Mickelson (1988) suggest that the gain in discharge may have been primarily due to the changes in watershed size and that downcutting may have been gradual, not necessarily catastrophic.

### Geography

The Valparaiso Morainic System is the youngest glacial feature eroded by overflow via the Chicago outlet. Minimum ages of features comprising the Valparaiso system include  $18,500 \pm 90$  cal yr BP (Valparaiso Morainic System; Curry et al., 2016),  $17,170 \pm 100$  cal yr BP (Tinley Moraine), and  $16,480 \pm 100$  cal yr BP (Lake Border Morainic System; Curry, 2015). The Chicago outlet is located about 40 km (25 miles) southwest of the city of Chicago, near Bolingbrook, IL (Figure 7). The Chicago outlet is comprised of two branches: the Calumet Sag channel to the south and the valley of the Des Plaines River, to the north. The Lake Border Morainic System was formed during part of the Glenwood Phase (Curry, 2015), although evidence of it is generally lacking in southernmost Lake Michigan basin (Figure 3).

### Geologic framework

The surficial, fossiliferous silty and clayey lacustrine deposits I examined are mapped as part of the Equality Formation (Willman and Frye, 1970; Hansel and Johnson, 1996). Although

defined by lithology, a tacit assumption is that much of these deposits are lacustrine and typically have features associated with that environment such as laminations and fossils of aquatic plants and animals. In my study area, these deposits are often associated with sandy and occasionally gravelly debris of alluvial or lacustrine origin mapped as the Henry Formation. Specifically, the origins of these deposits in my study area are (in order of fine to coarse-grained): sandy littoral or beach deposits, dune sand, and sand and gravel outwash. Deposits of peat (Grayslake Peat) and Holocene alluvium (Cahokia Formation) occasionally cover the surficial Equality and Henry units. Underlying these are glaciogenic deposits of diamicton interbedded with sorted sediment. The silt and clay matrix-supported diamicton of the Wadsworth Formation comprises the Lake Border and Valparaiso morainic systems, and is the oldest Quaternary unit of interest in this study. Silurian-age dolomite is exposed locally in and along the Chicago outlet and other valleys in the study area (Bretz, 1951; Curry and Bruegger, 2015).

#### Proposed study

The goal of this paper is to provide evidence for the age and duration of the Glenwood Phase and to help define its transition to the Calumet Phase. To perform this task, I chose three sites to examine in order to find suitable organics for radiocarbon assay. The sites were chosen to fulfill two primary criteria. First, the site located so that it captured sediments deposited during the highest stands of the Glenwood pPhase; second, the site needed to be located in a geomorphically favorable area conducive to preserving sediment successions. The three sites chosen were: Riggle Pond, Plum Creek and Harms Woods (Figure 1).

Prior to my work, the age of the Glenwood was based on only two ages (Hansel and Mickelson, 1988; Hansel and Johnson, 1996), whereas Hansel and Mickelson (1988) reported 10 radiocarbon dates from Tolleston level lake deposits, and 12 from Calumet deposits. I reject one

of Hansel and Mickelson's ages for the Glenwood Phase since it does not appear to correspond directly with any Glenwood features. The Glenwood date I accepted was collected from the type Glenwood beach ridge (the "Lynwood Reservoir" site; Table 2, Appendix B). The rejected Glenwood date is from the Tinley Reservoir site located in a proglacial lake not in contact with Lake Chicago on the toeslope of the Tinley Moraine, a feature that was eroded by the Chicago outlet. My study adds 22 radiocarbon ages (all but one determined by AMS) for the primary purpose of determining the span and age of the Glenwood Phase (Table 2, Appendix B). It should also be noted that the existing two radiocarbon dates were assayed by conventional methods (with attendant errors of about 405 yrs) compared to my dates (assayed with AMS, with errors of less than about 100 yrs).

The ~ 7 meter drop in lake level from the Glenwood to the Calumet could have been controlled by gradual changes in regional hydrology (Hansel and Mickelson, 1988) or it could have been a result of large, episodic floods that caused periodic incision of the Chicago outlet (Bretz, 1955). If the sediment accumulation rate throughout the phase change from Glenwood to Calumet did not vary significantly, the downcutting was most likely a gradual change, meaning Hansel and Mickelson would most likely be correct. Geomorphic evidence presented by Kehew (1993) indicates catastrophic discharge and rapid downcutting. The evidence includes boulder lags (since removed for barge traffic) in the Calumet Sag Channel consistent with lakeward knickpoint migration (Bretz, 1951; Kehew, 1993). Kehew (1993) also noted that "shoreline features of each lake level converge to separate outlet sills that decrease in elevations from the oldest to youngest lake phases." Kehew (1993) speculated that the megaflood in the Grand River Valley was a consequence of retreat of the Saginaw lobe during the waning of the Port Huron phase which made accessible overflow of Lake Whittlesey (proto-Lake Erie) and Lake Saginaw

to the Grand Valley and thence Lake Chicago. For the purposes of this study, if the sediment accumulation at the investigated field sites drops significantly the most likely model for lake level stabilization is the one suggested by Bretz. If Bretz's model is correct, the evidence for a large flood at the end of the Glenwood Phase should also be seen in the Illinois River Valley and possibly in the Gulf of Mexico following the meltwater from Lake Chicago.

A geomorphological feature that is critical to understanding the transition between the Glenwood Phase and the Calumet Phase is the Griffith spit. The Griffith spit (Figure 8) is comprised of several spit ridges that decrease in elevation northward (i.e. the fingers closer to the Calumet shoreline are lower in elevation than the ones closer to the Tinley Moraine), though it is hard to determine exact ridge elevations because of the urbanization of the area. The axes of the ridges progressively rotated lakeward to the north. Each ridge was likely formed during a period of lake level stability. If OSL dates for each spit ridge were obtained, it would provide conclusive evidence for how fast lake levels fell during this time. The ages can be correlated to their respective ridge elevations and a model could be created. Dating this geomorphological feature would also provide new evidence regarding the nature of how these features were formed.

Riggle Pond was chosen to investigate because it is located between spit ridges of the Griffith Spit and because it has been previously cored by Todd Thompson who informed us that he had cored a thick, fossiliferous lacustrine succession, but the core had been disturbed during transport and curation, and rendered useless. Located at an elevation of ~194 m, a significant drop in the level of Lake Chicago between the Glenwood and Calumet phases (195m to 189 m) ostensibly would be recorded in a sediment core.

Another key site in my study in the middle reaches of Plum Creek was first discovered by J. Harlen Bretz in the 1930's (Figure 9). His outcrop descriptions include tantalizing clues that a lagoonal sediment record graded to Lake Chicago. Here, he described thin fossiliferous marl and lacustrine sediment that overlapped a lag of gravel above glaciogenic diamicton (till; Bretz, 1955). Bretz published photographs of the site, and of several of the fossils which included branches, cones, (deer) antlers, and a worn mastodon tooth. Two separate sites were cored in the low-lying uplands adjacent to Plum Creek. Shaded relief maps of digital elevation models (DEMs) using LiDAR data available from the ISGS, revealed a broad, shallow depression with a lip elevation of about 193.5 m (Figure 9). Today, the depression is a shallow wetland demarcated by peaty soils, and surrounded by soils developed in silty-clayey till (Calsyn , 2012), and is interpreted to be a kettle lake. The ISGS rented a tread-mounted GeoProbe which I used to core the edges of the wetland with the theory that this basin captured lacustrine sediment from the highest stands of the Glenwood Phase. The last site investigated at the Plum Creek Preserve (PC 5) is located in a low, flat area immediately adjacent to the creek, about 300 m east of the Tinley Moraine, and almost due west of the kettle site. The flat area was likely filled with lagoonal sediment associated with Lake Chicago, which was later confirmed through examination of sediment cores sampled at the PC-5 site (Figure 9).

The last site chosen is located on the west side of the Wilmette spit. Harms Woods Forest Preserve is farther north than the other two sites (Figure 6) and is within an area called Skokie bay landward of the Wilmette spit (Bretz, 1955), another important Glenwood shoreline feature (Figure 8). The Wilmette spit is also proximal to the Rose Hill spit, which is a key Calumet feature. Many important dates that define the age of the Calumet came from the Rose Hill spit

(Schneider and Hansel, 1990), which reinforced my choice to look for Glenwood-aged material at Harms Woods

A fourth site was investigated in the early stages of my research, but the results are more germane to understanding the Nipissing Phase of Holocene Lake Michigan. The site was located at Moraine View Community College (MVCC; Figure 10) and it was investigated as part of a surficial geology mapping project done through the Illinois State Geological Survey. The site included a series of very detailed report of sediment logs of cores sampled on a 100-ft grid over an area of about 0.25 square miles. The report, done in 1955, characterized the materials for a parking lot for a proposed department store which was never built--instead arose MVCC. I examined 3 cores sampled with the ISGS PowerProbe. The site is located in a wide channel with a surface elevation of about 180 m, clearly much lower than either the Glenwood or Calumet levels, but consistent with the Tolleston level. Radiocarbon ages obtained from plant macrofossils (mostly *Schoenoplectus* seeds) indicate the onset of the Nipissing Phase occurred from about  $6400 \pm 50$  to  $5920 \pm 50$  cal yr BP).

## METHODS

In September 2014 a five meter length core was sampled with a Livingston piston corer in Riggle Pond, located in Oak Ridge Prairie State Park in Griffith, Indiana (Figure 3). The corer was operated from a platform that was secured to two inflatable kayaks. The core was extruded in the field, wrapped in cellophane and aluminum foil, and stored in a cold room at UIUC at 4°C. The core has a diameter of 5 cm. A duplicate core was sampled from 540-640 cm due to an error in the coring process. The duplicate core was sampled about 1 m away from the main site. Core recovery was very good, at least 90% for each drive. Drive number two, the drive that was compromised during sampling, had 68% recovery.

Each drive was pushed one meter. Each core drive was split in half, described and photographed (Appendix 1) Once the descriptions were finished, one half of each drive was divided into ~5cm sections to be washed for fossils. Core material was pretreated with boiling tap water. The sediment slurry was then wet sieved through 150 µm openings. The residue was placed in petri dishes, dried, and the picked with a fine brush under a dissecting microscope. Fossils were stored in vials with about three drops of 18% HCl. The fossils selected for dating were cleaned again and photographed using a 3.3-megapixel digital camera mounted to a trinocular dissecting scope (Appendix B). Several sections had adequate material for radiocarbon dating, including needles, and fragments of charcoal and wood. I emphasized dating horizons that represented the hypothesized top and bottom of the Glenwood Phase, as well as the base of the Calumet Phase, based on subtle changes in lithology and organic matter content.

A GeoProbe 6600 track-mounted hydraulic push-probe was selected for sampling sediment cores. The probe was contracted to the ISGS from Terra Probe Environmental (Ottawa



Lake, Michigan). This machine was needed because the area surrounding Plum Creek is swampy and inaccessible with equipment owned by the ISGS. The core tube diameter was 1 3/8". The drilling rig is remote-controlled, and travels on treads which is less damaging to wet or soft soils.

In search of an outcrop described by Bretz (1951), I examined exposures along Plum Creek between State Road 30 and Steger Road. Based on Bretz's published photographs, I believe I rediscovered the outcrop where I acquired sediment samples and one tree stump for radiocarbon assay.

Grain size analysis was performed using a Mastersizer 3000 housed in Dr. Jessica Conroy's lab (Plant Biology and Geology, UIUC). Subsamples (~5 grams) were pretreated by oxidizing organic matter with hot (50° C), dilute 30% H<sub>2</sub>O<sub>2</sub> overnight. Next, deionized water was added to each sample tube so the fluid level was equal and placed in a centrifuge at 5000 RPM for 3 minutes. The supernant was decanted, and the process repeated two more times. Before the prepared samples were placed into the Mastersizer for analysis, dispersant was added, and sample gently agitated to ensure the sediment was in suspension (Appendix D).

To help characterize the Glenwood and Calumet deposits, I determined the relative, semi-quantitative mineralogy of the clay-sized fraction using XRD methods on oriented, glycol-solvated slides (Hughes et al., 1996; Curry and Grimley, 2006). In particular, I was interested in determining if any far-traveled loess, which is rich in smectite, had become part of the lake sediment which ostensibly was initially illite and chlorite-rich, mimicking the mineralogy of the underlying till units (Graese et al., 1988). Unfortunately, not all of my samples were analyzed due to XRD equipment failure, but I obtained results from the Moraine Valley Community College, Plum Creek and Harms Woods sites. The content revealed at each site illite was the

major clay mineral component with little variation. The results indicated that little to no far-traveled loess was incorporated into Glenwood Phase Lake Chicago sediment.

Samples picked for radiocarbon assay were weighed to ensure adequate size for maximum age precision. Previous work indicated at least 0.17  $\mu\text{g}$  of wood, needles or charcoal was sufficient to obtain an age of ca. 15,000 cal yr BP with errors less than 60 years. The samples were pretreated by Dr. Hong Wang (Illinois State Geological Survey) who loaded and combusted the material in glass tubes; the released gasses were filtered chemically and thermally, and the purified  $\text{CO}_2$  pressurized and stored in canisters. The samples were further treated and assayed at the Keck AMS laboratory at the University of California-Irvine. The radiocarbon aged procures have both ISGS- and UIUCAMS- laboratory numbers. The results were calibrated using Calib7.1 (Stuiver and Reimer, 1993) using IntCal13 (Reimer et al., 2013).

## RESULTS AND DISCUSSION

The Riggle Pond core provided the most important sedimentological data for my project. Water depth was 4.4m and the sediment core bottomed out at 9.4 m in fossiliferous, very well-sorted medium sand. Three lithologic units, all classified with the Equality Formation (Hansel and Johnson, 1996) overlie the sand, including (1) a dark gray silt loam unit from about 9 m to about 5.8 m, (2) a unit of firm, organic-rich loam 8.4-5.8 m and (3) soft, soupy peat (5.8-4.4 m). A detailed core log is in listed in Appendix A1.

The major conclusions of my study are possible through 22 new AMS radiocarbon ages, and one conventional radiocarbon date (Table 2, Appendix B). There was no useful dateable material found in the sediment cores sampled at Harms Woods, but the remaining two sites (Riggle Pond and Plum Creek) yielded abundant organic matter for C-14 assay, primarily needles and rootlets. Riggle Pond yielded dates that range from 16,184 to 13,385 cal yr BP, which overlaps earlier age determinations of the Glenwood and Calumet phases (Hansel and Mickelson, 1988). The three sites at Plum Creek yielded dates from 15,730 to 17,210 cal yr BP, which covers most of the Glenwood Phase, and provides excellent evidence for the onset of the Glenwood Phase of Lake Chicago (16,800 cal BP), and minimum age for the Tinley Moraine (17,200 cal yr BP; Table 2, Appendix B). The C-14 ages indicate an approximate 1000-year gap between the Glenwood and Calumet phases. Abrupt shifts in sediment accumulation rates at Riggle Pond argue for similarly abrupt downcutting of the Chicago outlet reflected in the 7-m dropdown in lake level during the transition from Glenwood to Calumet levels.

In addition to the lake level drop between the Glenwood and Calumet phases, published evidence suggested an intra Glenwood Phase named the Mackinaw low (Figure 12; Monaghan

and Hansel, 1990) that separated the Glenwood I and Glenwood II subphases. Little, if any, change in maximum lake level was inferred between Glenwood I and Glenwood II (Figure 12; Chrzastowski and Thompson, 1992). The lower lake levels of the Mackinaw low are attributed to opening of the Straits of Mackinaw by a receding Lake Michigan lobe (Monaghan and Hansel, 1990). There is only radiocarbon assay that dates the Mackinaw low, organics sampled at the Riverside site located along the Lake Michigan shoreline in southwestern Michigan.

One C-14 assay was judged unreliable (ISGS-A3466). The material used to obtain that date (Figure 22 in Appendix B) had low mass and was composed of unidentifiable material; the other (reliable) samples from Riggle Pond were either needles, grass stalks, or small, blocky fragments of charcoal.

Analysis of the Riggle Pond radiocarbon ages yielded a useful age model created by Bayesian statistics. The age models were created using the program and methods described in Blaauw and Christen (2011). Riggle Pond was the site with the most complete history, including most of the the Glenwood Phase and onset of the Calumet Phase). The Plum Creek ages were useful in confirming the approximate onset of the Glenwood Phase (Figure 11).

Outputs from the Bacon program were used for the determination of sedimentation rates, which is of special interest to this study. This was done by taking the first derivative of the age-depth model. The age depth model created shows the interpolated age of material with respect to its depth. The first derivative of this model produces the rate of sediment accumulation change and can be re-plotted with respect to age (Figure 14). The plot emphasizes differences in value and uncertainty in the sedimentation rate and shows the sedimentation rate change. If the transition from the Glenwood to the Calumet level was not catastrophic and was solely controlled by regional hydrology changes, this should be reflected by having a nearly constant

sedimentation rate. Instead, what is observed is a ca. 1,000 yr long period (ca. 15,100 to 14,050 cal yr BP) of low sedimentation rate of 0.1 cm/yr sandwiched by periods of higher sedimentation rates of about 0.135 cm/year or higher (Figure 14). Changes in the water depth of Riggle Pond likely reflected changes in Lake Chicago levels owing to the narrow sandy spit ridge separating them.

I speculate that the decrease in the sediment accumulation rate was caused by a period of lower lake levels in Riggle Pond that led to less wave power and sediment movement. Lower lake levels and attendant smaller lake surface area would have led to a shorter fetch, consistent with waning wave-driven currents. A drop in lake level may have been hastened by a catastrophic influx of water from drainage of eastern proglacial lakes into Lake Chicago via the Grand River valley (Figure 4). Recall that the presence of the Chicago outlet means that Lake Chicago was hydrologically open, meaning that lake levels could not rise above levels previously established during the Glenwood Phase, but the additional discharge likely resulted in erosion of the nearby Chicago outlet. This scenario explains the downdrop of lake level at about 15,100 cal yr BP, but cannot account for persistently low lake levels until the re-expansion of Lake Chicago during the Calumet Phase at 14,200 cal yr BP. This period of low lake levels may be accounted for by opening of northern outlets by waning glaciers, low meltwater production rates, or a period of subglacial meltwater accumulation.

Grain size analysis show that the lake sediment is composed of mostly silt. Material of this size settles out in a 10-m water column in less than 10 minutes. The maximum water depth of the core site was 9 m. Considering the maximum altitude of Glenwood features (Chrastowski and Thompson, 1992), the elevations of key stratigraphic markers in the sediment core (Figure 12) and the protected location of my coring site, which would have blocked littoral currents,

indicates that the material is from a local source and probably reworked till. Sediment deposited during the Glenwood Phase shows considerable variability in the coarse: medium silt ratio (32-64  $\mu\text{m}$  versus 16-32  $\mu\text{m}$ , respectively) (Figure 15). A ratio of about one is indicative of poor sorting and consistent with a local sediment source. During the period between the Glenwood and Calumet phases, coarse silt is dominant. Calumet Phase-age sediment is more influenced by medium silt, and the values are much less variable than the Glenwood-age samples. I interpret these changes, in part, to the proximity of the ice margin. In Glenwood times the Lake Michigan lobe was located not far from Riggle Pond, although the exact location is not known. Blue Island, for example, is a water-washed remnant of a Lake Border Moraine (Figure 3). Radiocarbon evidence from an ice-walled lake plain in Wadsworth, Illinois, indicates active ice at about 16,400 cal yr BP (Curry and Petras, 2011). The glacier itself was not likely responsible for the variability in silt ratios, but instead, instability may have been caused by increased storminess and water turbulence associated with unstable climate over the glacier margin. In addition, the change in silt size variability between the Glenwood and Calumet can be interpreted as a change in Riggle Pond's morphology. During the Glenwood Phase, Riggle Pond may have been part of Lake Chicago, although protected somewhat by the spit ridge. After lake levels rebounded during the Calumet Phase to an altitude about 7 m lower than the Glenwood, Riggle Pond was a hydrologic feature separate from Lake Chicago. Riggle Pond continued to accumulate sediment during the Calumet Phase, but from a more local, stable source, likely under less stormy and variable conditions. Overall, however, the coarse: medium silt ratio hovers around one, indicating a local source; any variability can be interpreted as a change in Riggle Pond's variability.

## CONCLUSION

The results of my findings can be distilled into the following:

- I have evidence for the existence and timing of the Mackinaw low, separating Glenwood I and Glenwood II
- My findings are more consistent with Bretz's original theory of episodic downcutting
- I have evidence of a sedimentological disturbance at around 15.1 ka and I have interpreted this disturbance as a meltwater flooding event that originated from the LIS
  - My recorded disturbance aligns with other flooding evidence found in the Lower Mississippi River Valley and the Gulf of Mexico
  - The sedimentological disturbance signifies the end of the Glenwood Phase

In the southern Lake Michigan basin, after forming the Tinley Moraine, the Lake Michigan lobe retreated north prior to 17,200 cal yr BP. Meltwater pinned between the retreating glacier and moraine was the beginning of proglacial Lake Chicago. Initially, the lake was small as the glacier fluctuated forming the Lake Border Moraines at about 16,500 cal yr BP (Curry, 2015). My radiocarbon age evidence from the Plum Creek sites is consistent with the date of Hansel and Johnson (1992) that the highest level of Lake Chicago occurred between about 16,700 and 16,800 cal yr BP. The Riggle Pond record begins at about 16,180 cal yr BP (there is likely older material that I was unable to penetrate due to the high sand content) and suggests constantly high lake levels until  $15,150 \pm 70$  cal yr BP, which I interpret to be the end of the Glenwood Phase. A subtle gap in the probability density function of the radiocarbon chronology offers some support for the Mackinaw low of at about  $16,220 \pm 220$  cal yr BP (Monaghan and Hansel, 1990; Figure 16). Between  $15,150 \pm 70$  and  $14,050 \pm 50$  cal yr BP, Riggle Pond levels, and hence Lake Chicago, likely dropped below an elevation of 187 m. After that time, lake levels rose during the Calumet Phase; regional data indicate high lake levels of about 189 m (Schneider and Hansel, 1999).

My scenario described above is consistent with Bretz's (1951) hypothesis that there was rapid downcutting between the Glenwood and Calumet phases. Bretz and subsequent researchers (i.e., Hansel and Mickelson, 1988; Chrzastowski and Thompson, 1992) could not have anticipated a ca. 1,000-year gap between the two phases due to a paucity of radiocarbon ages for the span of the Glenwood Phase. The gap suggests low lake levels during that time suggesting either an opening of a northern sill, such as the Straits of Mackinaw, lesser effective moisture (climatic conditions), or storage of subglacial meltwater. Perhaps the latter conditions occurred after the catastrophic release of meltwater that accounts for the geomorphic and sedimentological evidence of a large flood in the Grand River valley at the mouth of the Chicago outlet (Kehew, 1993). The hypothesis of Hansel and Mickelson (1988) does not appear to explain my findings or those of Kehew (1993). They attributed higher lake levels to added meltwater discharge from the eastern Lake Michigan, Saginaw, and Erie lobes via the Grand River valley (Figure 5), but my findings suggest it is more likely that the Grand River valley connection existed after the Glenwood Phase and not prior to it.

The sedimentological and chronological data from Riggle Pond indicates significant hydrological change at about 15,100 cal yr BP, consistent with evidence of a major flood in the middle Illinois River valley at 15,200 cal yr BP, and Aharon's (2003) 15,000 yr BP Meltwater Flood 3 from the Orca Basin. The latter feature is notable because of a remarkable increase in redeposited nannofossils, indicative of deep-water erosion (Marchitto and Wei, 1995). This evidence corroborates my speculation that the dropdown from Glenwood to Calumet levels was initiated (at the end of the Glenwood) by a large flood, likely the one envisioned by Kehew (1993) that coursed down the Grand River valley. This flood had immense erosional capability as it formed lemniscate terrace remnants in the Grand River valley, and boulder lags in channels



feeding the Chicago outlet. Moreover, it downcut the Chicago outlet about 7 m, carved a ca. 50 m deep channel in the Illinois River valley, temporarily eroded the Savanna-Deerfield terrace at the mouth of the Illinois River, deposited the Kennett braid belt terrace in the lower Mississippi River valley (Rittenour, 2005), concentrated nanofossils in sediment accumulating on the north slope of the Orca Basin (Marchitto and Wei, 1995) and consequently produced a 1.5‰ excursion in the  $\delta^{18}\text{O}$  record (Aharon, 2003; Figure 16). Interestingly, all chronological evidence of this flood (which varies from 15,000 to 15,200 cal yr BP with ca. 100 yr error) precedes Termination I by about 350 yrs. Perhaps the flood that occurred at the end of the Glenwood Phase was “nudging” factor that helped to bring on Termination I.

# FIGURES

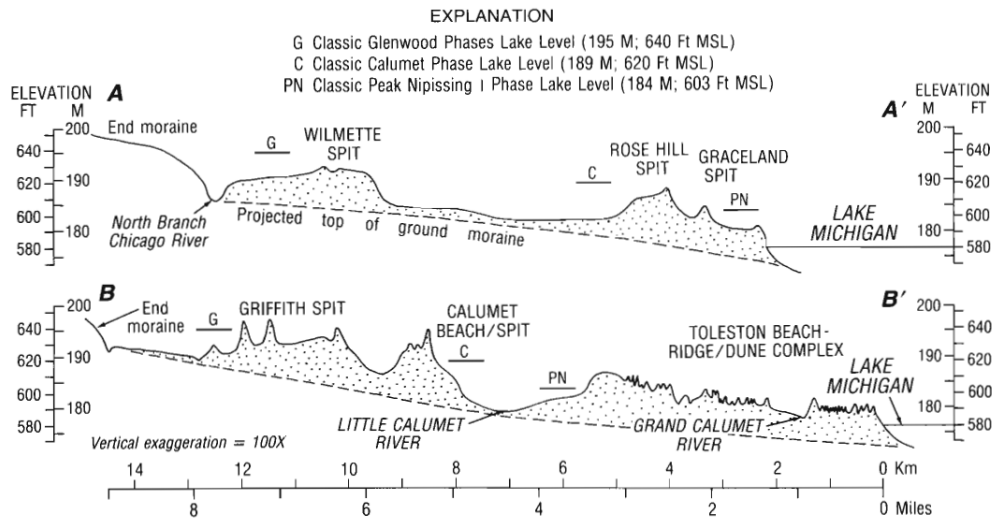


Figure 1: The “successively lower elevations of spits and beach ridge/dune systems of the Chicago/Calumet lacustrine plain (Chrzastowski and Thompson, 1992). The cross section lines are located in Figure 6.

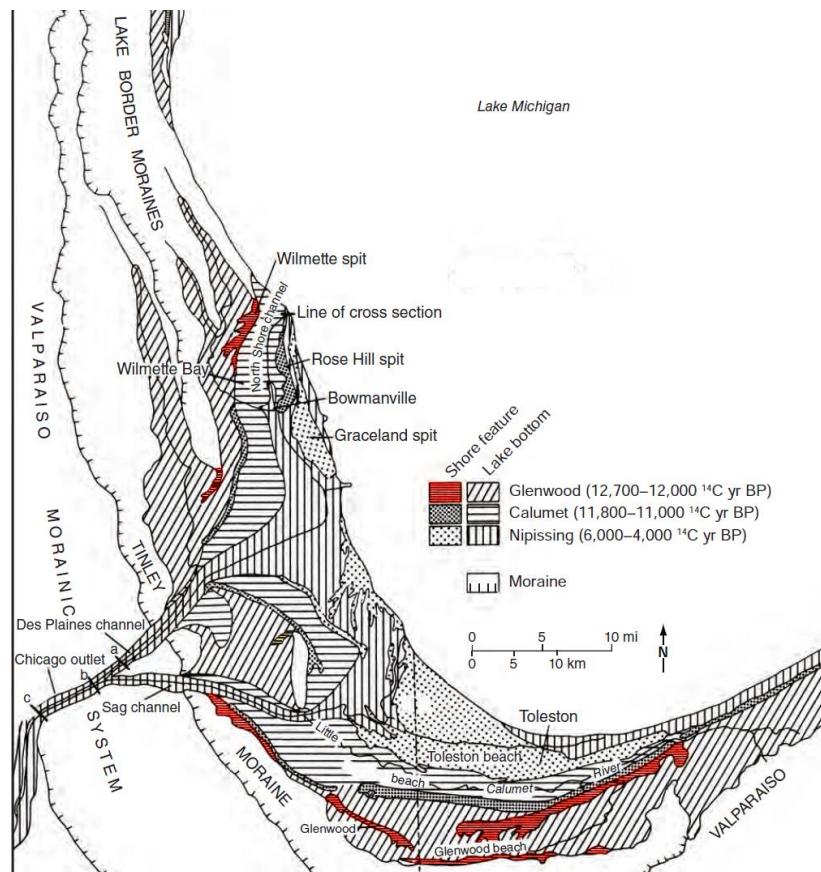


Figure 2: Surficial deposits of Lake Chicago and Michigan. The shoreline features associated with the Glenwood Phase have been highlighted in red (modified from Hansel and Mickelson, 1988).



Figure 3: Location of key sites discussed in my study. (Map created using data and basemap available via ArcMap Online)

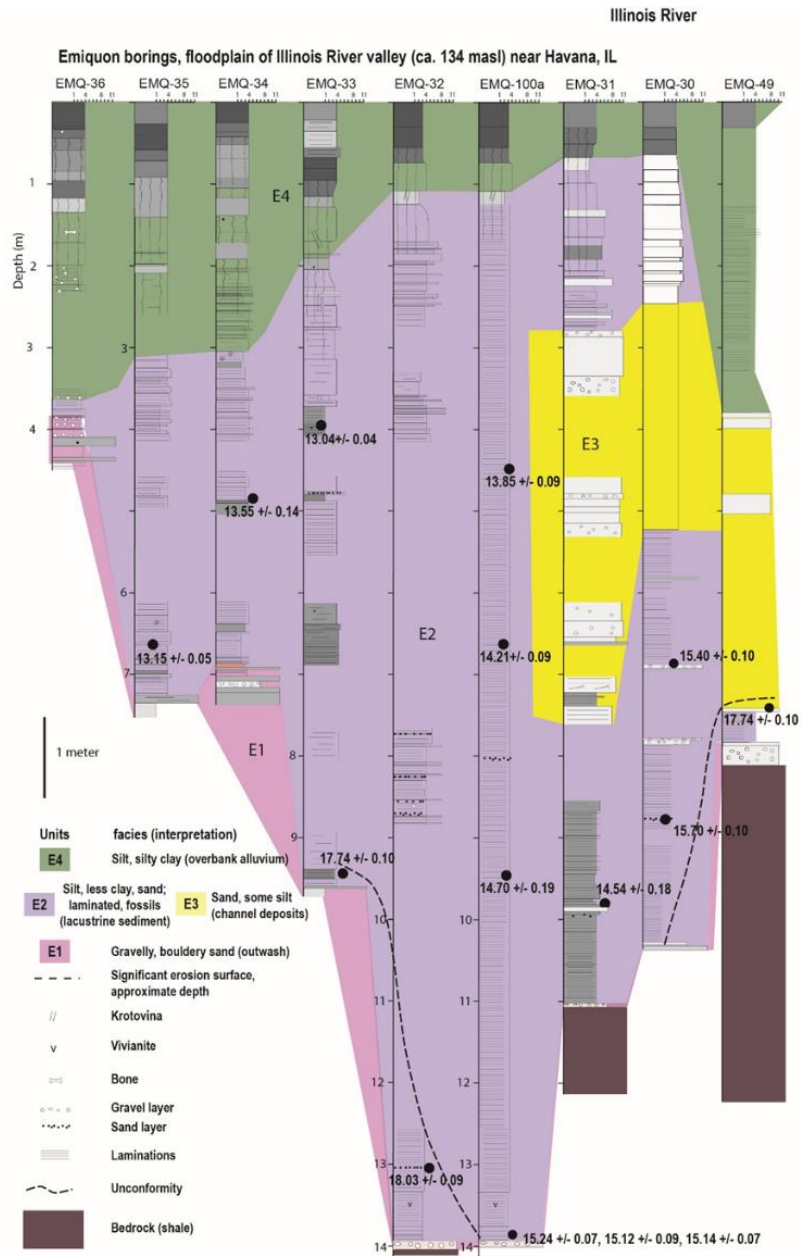
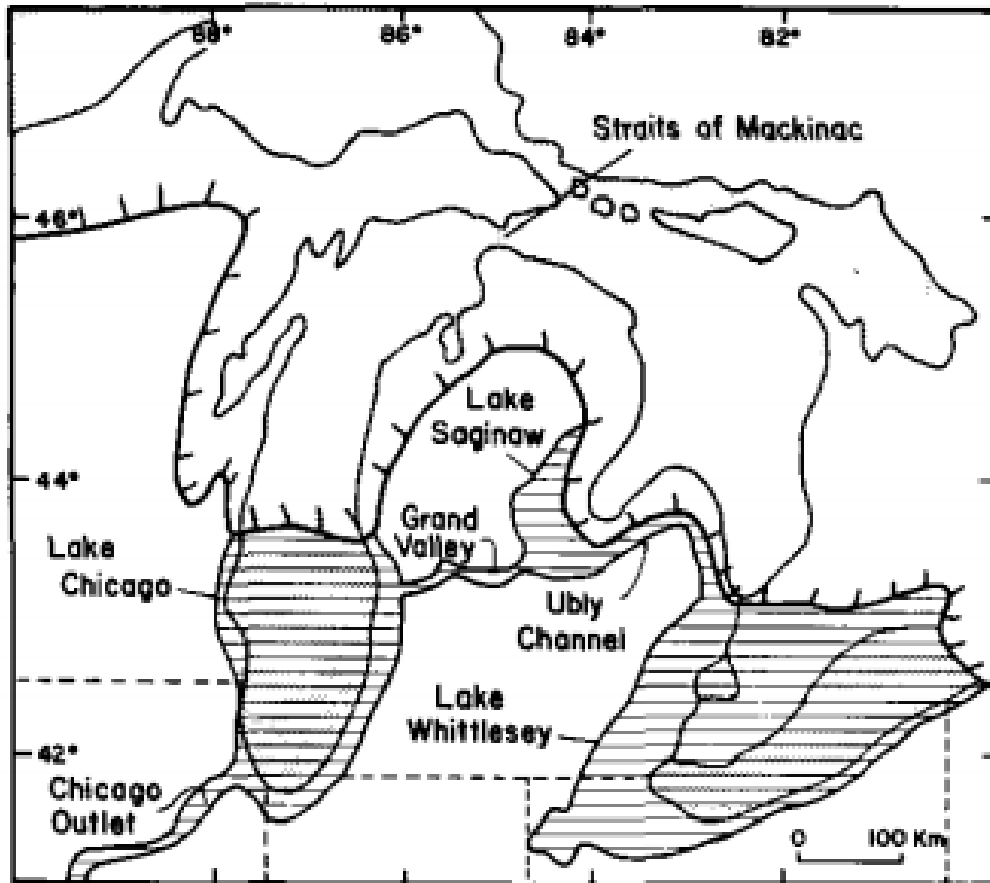


Figure 4: Valley-fill deposits at Emiquon refuge highlighting radiocarbon ages of plant fossils archived in lake sediment at the base of scoured channels with minimum ages of 18.03, 15.70, and 15.24 ka .24 ka (modified from Curry et al., 2014).



**FIG. 1.** Map showing location of proglacial lakes in Lake Michigan and Lake Huron basins. Ice margin shown at limit of Port Huron Advance (12,900–12,700 yr B.P.).

Figure 5: Kehew 1991. Conditions during the Glenwood Phase (Kehew, 1991) showing the connection between Lake Whittlesey via the Uby channel, Lake Saginaw, and Grand Valley to Lake Chicago. Meltwater feeding Lake Chicago thus included meltwater from the Huron, Saginaw, Erie and Lake Michigan lobes. Sometime between the Glenwood Phase and the Calumet Phase, the Grand Valley outlet no longer conducted meltwater through the Grand Valley, thus cutting off meltwater contributions except from the Lake Michigan lobe. Hansel and Mickelson reasoned that this major change in hydrology and water input to Lake Chicago may have been the primary driver of lake level change.

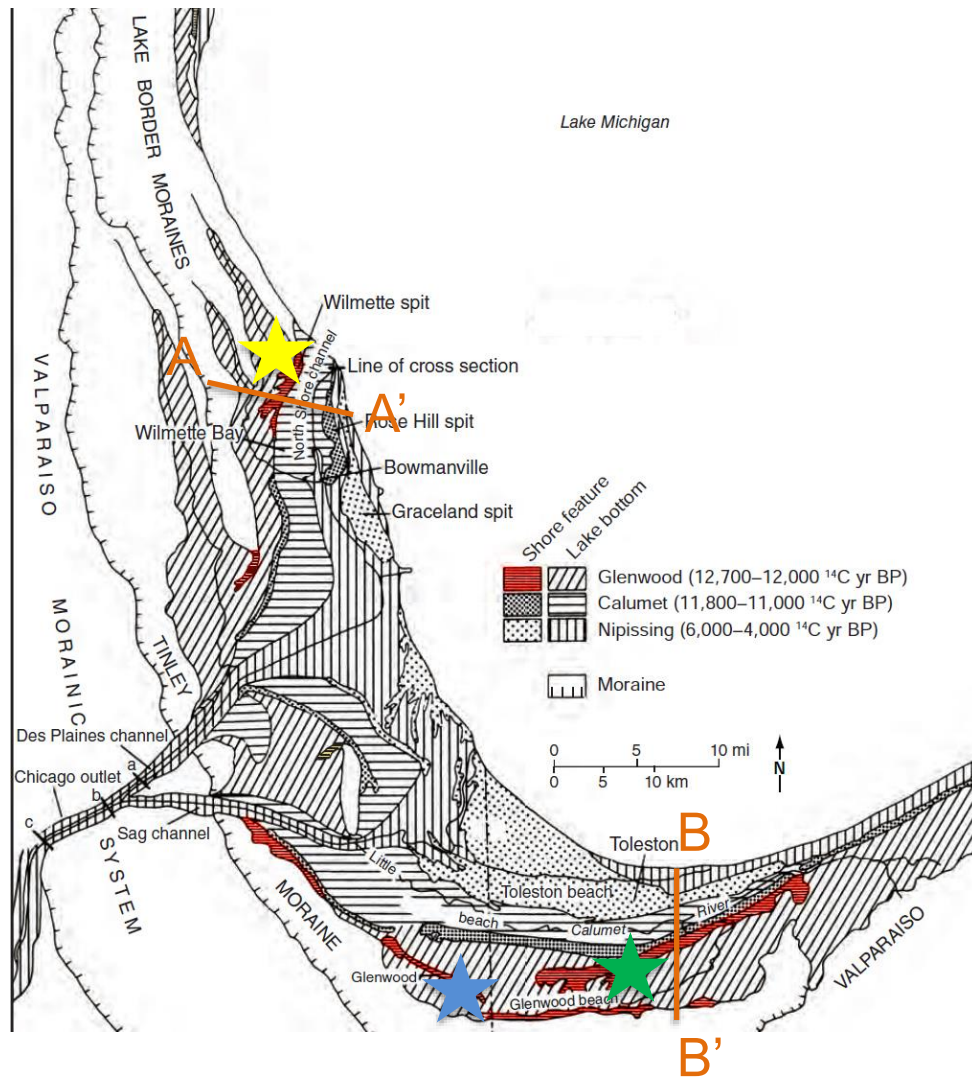


Figure 6: The locations of lines of section for Figure 5, and study sites including Harms Woods (yellow star), Plum Creek (blue star) and Riggle Pond (green star).

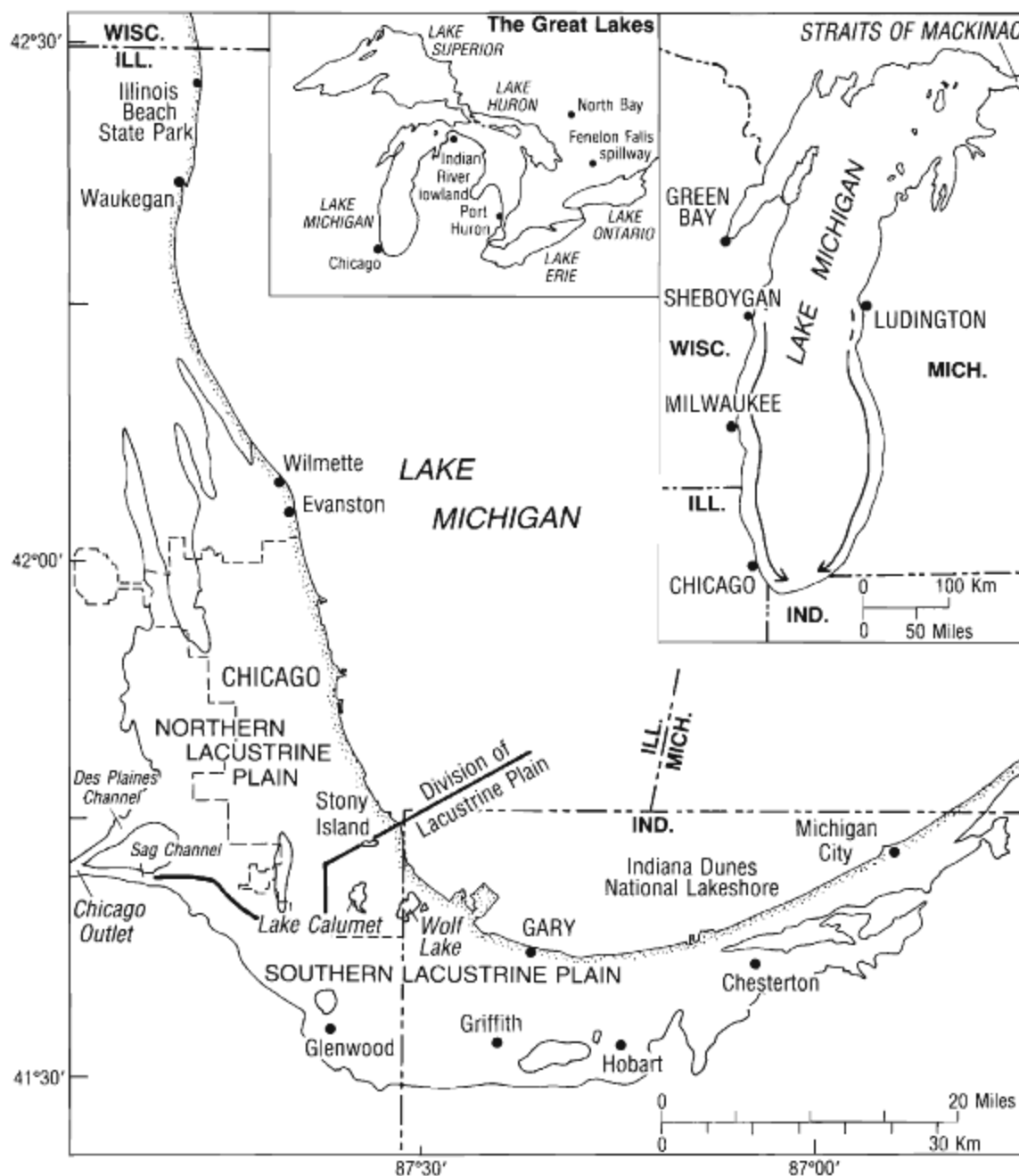


FIG. 1.—Location map of the Illinois/Indiana shore of southern Lake Michigan showing extent of the Chicago/Calumet lacustrine plain and its division into northern and southern parts. Lake Michigan inset shows extent of natural-state, net-southerly littoral transport along the western and eastern lakeshores.

Figure 7: The region surrounding the Chicago Outlet (Chrzastowski and Thompson, 1992).



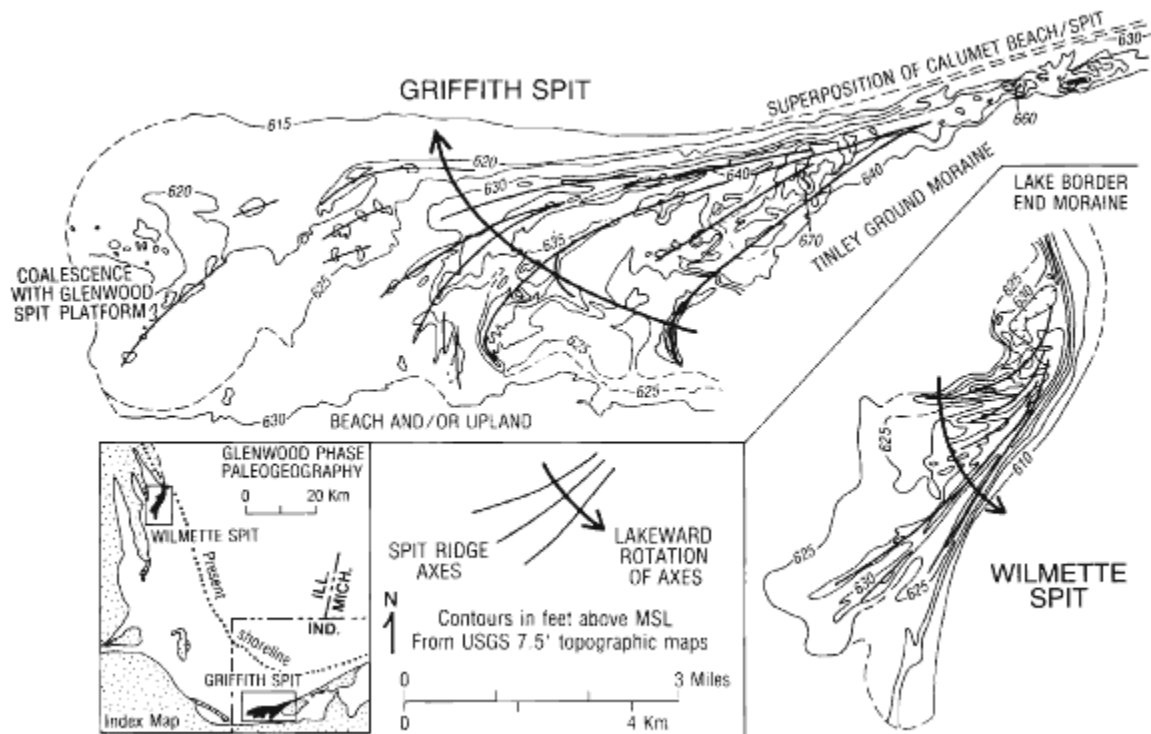


Figure 8: Contours showing the “lakeward rotation of the axes of the successively younger spit ridges.” (from Chrzatowski and Thompson, 1992).

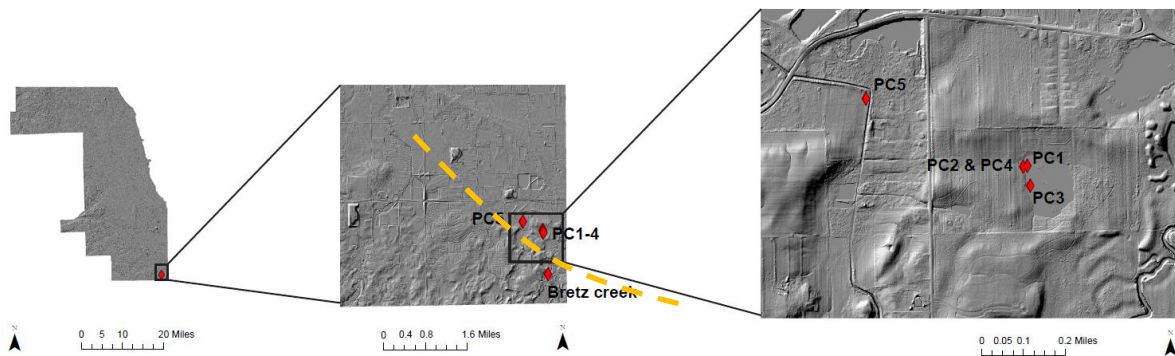


Figure 9: Locations of the Bretz site and sediment cores obtained from the Plum Creek locality. The basemap is a hillshade map of a DEM based on Lidar data. The leftmost figure displays all of Cook County. Sites PC 1-4 are where sediment cores were sampled on the margins of a kettle, today occupied by a shallow wetland. The dashed orange line in the middle diagram shows the location of Glenwood beach.



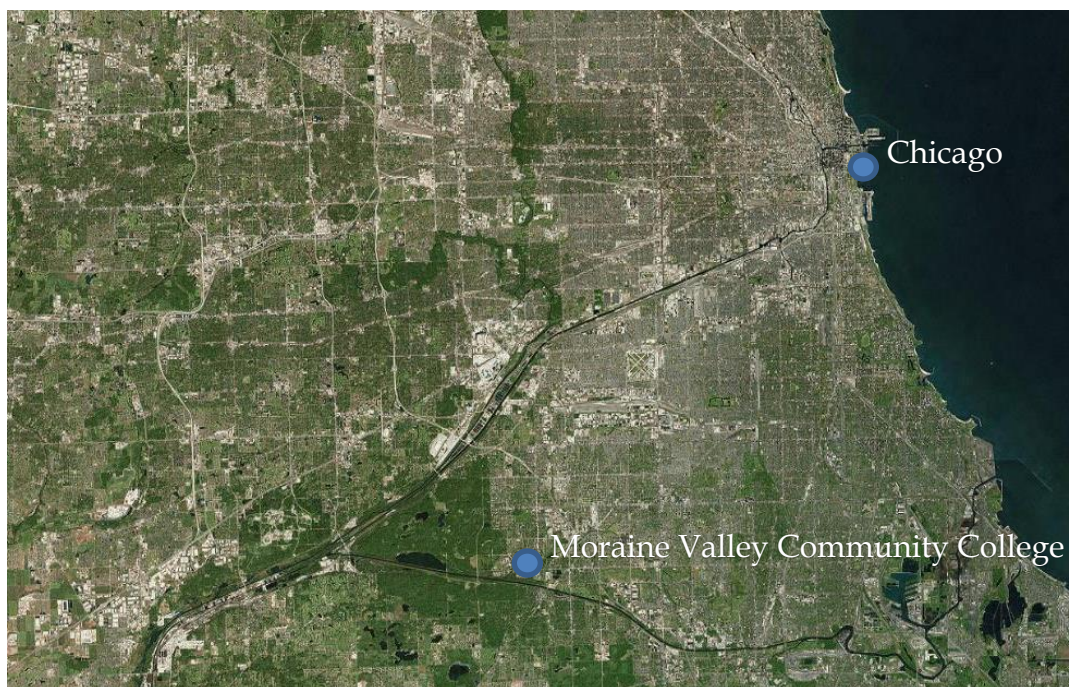


Figure 10: Location of Moraine Valley Community College, a site investigated early during this study. The site records a sediment record deposited during the Nipissing Phase. Aerial photograph available online from the USGS.

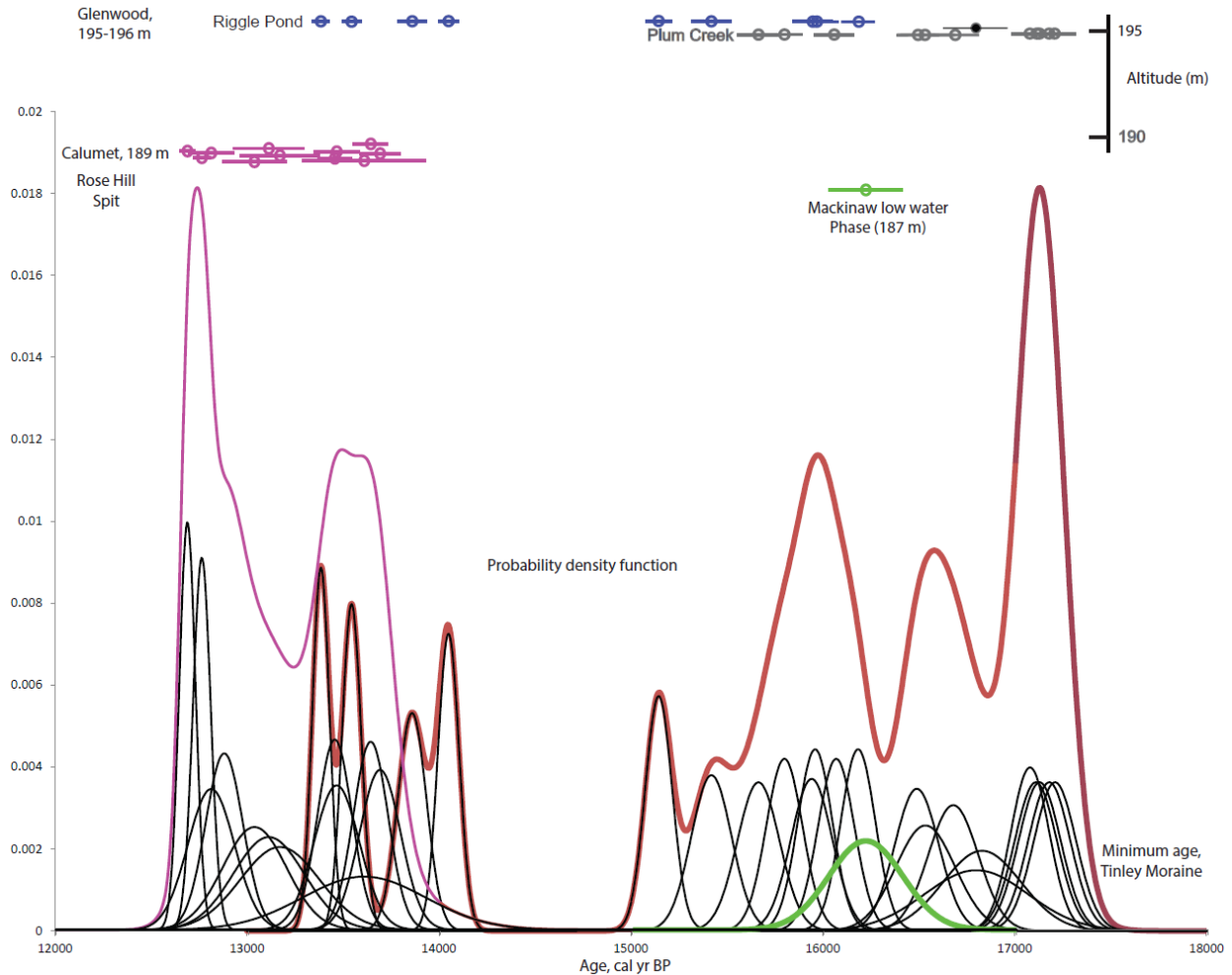


Figure 11: Radiocarbon dates from Plum Creek and Riggle Pond (this study), Schneider and Hansel (1990) and Monaghan and Hansel (1990). The black lines are individual calibrated radiocarbon assay results, and the red lines are the probability density functions of all ages. The radiocarbon age data were simplified to normally distributed curves. The specific dates and their relative elevation are shown at the top of the figure. Note the lack of ages between the Glenwood and Calumet phases. Evidence for the Mackinaw low is indicated by a lack of dates between the hypothesized Glenwood I and Glenwood II subphases.

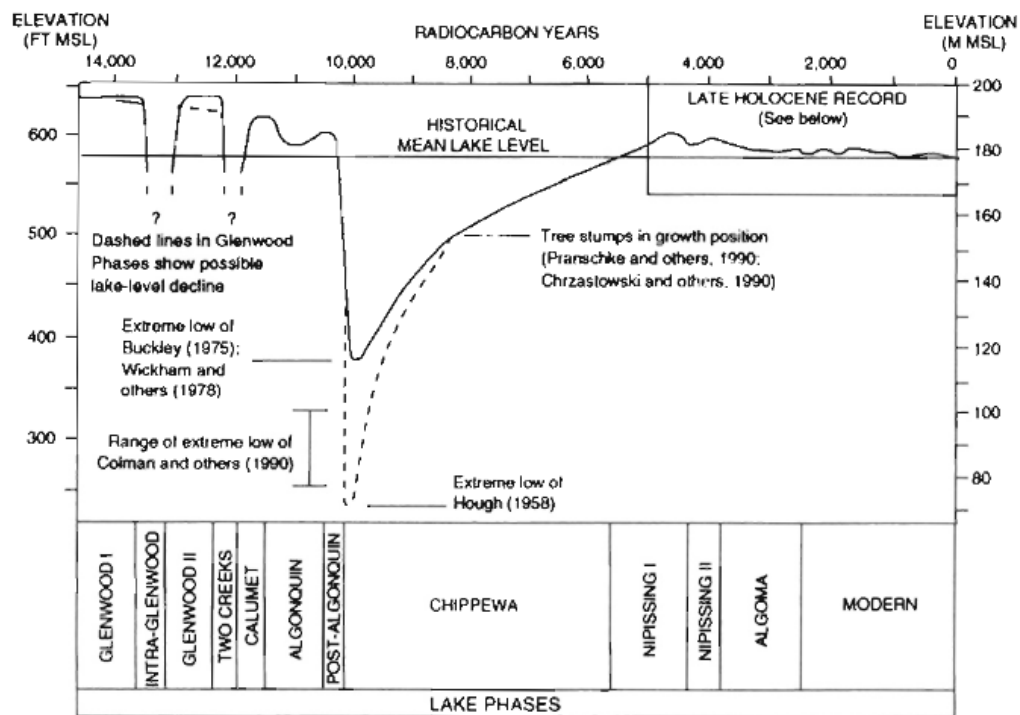


Figure 12: Summary of lake levels of Lake Chicago (Glenwood I through Algonquin phases) and Lake Michigan (Chippewa Phase through modern). The dashed line shows the magnitude of minimum uncertainty. from Chrzastowski and Thompson, 1992.

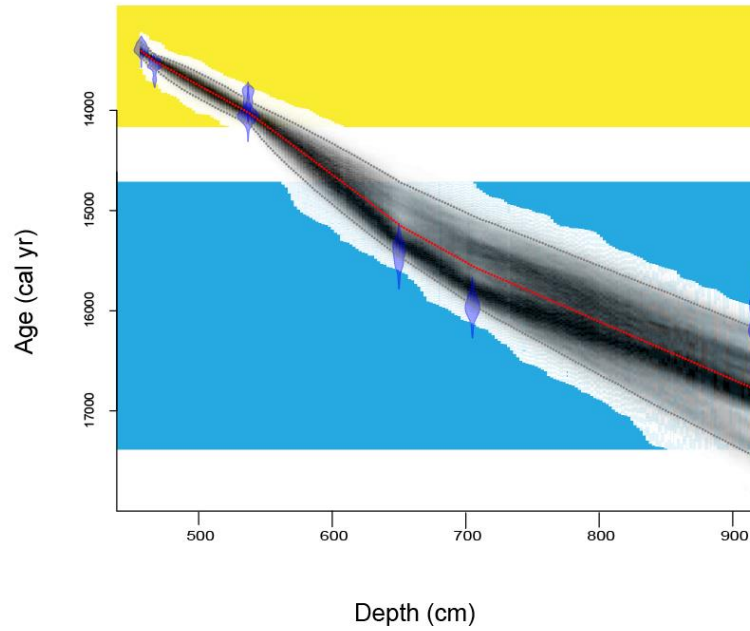


Figure 13: Age-depth model for the Riggle Pond site. Blue section spans the Glenwood Phase. Yellow section spans the Calumet Phase. Thin red line represents the median age. The black and gray space that follows the red line represent the calibrated age within two sigma error.

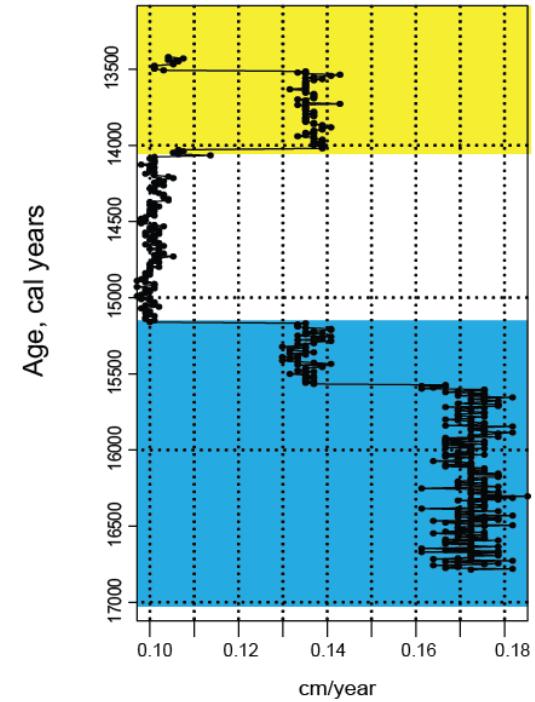


Figure 14: Sediment accumulation rates of Riggle Pond based on the first derivative of data comprising the age model, Figure 13. Blue section spans the Glenwood phase. Yellow section spans the Calumet Phase

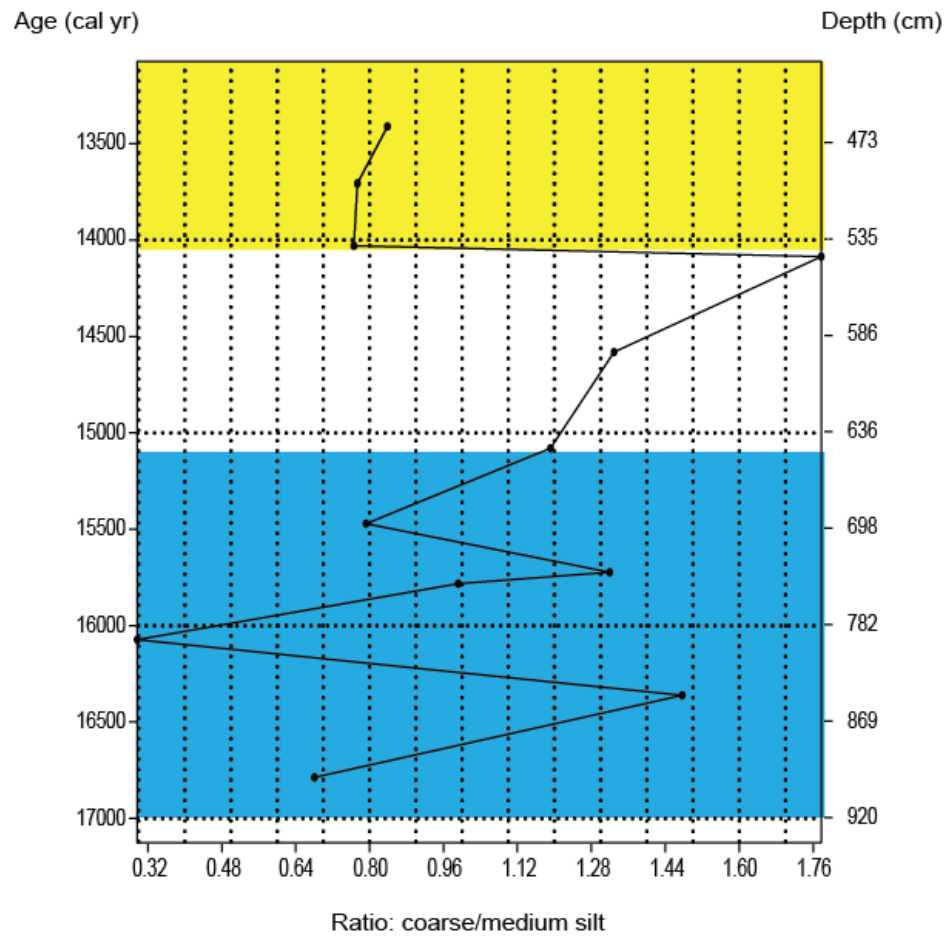


Figure 15: Change of the coarse: medium silt ratio over time. Coarse silt is 64  $\mu\text{m}$  – 128  $\mu\text{m}$ ; medium silt is 32  $\mu\text{m}$ -64  $\mu\text{m}$ . Blue section covers the Glenwood Phase. Yellow section spans the Calumet Phase.

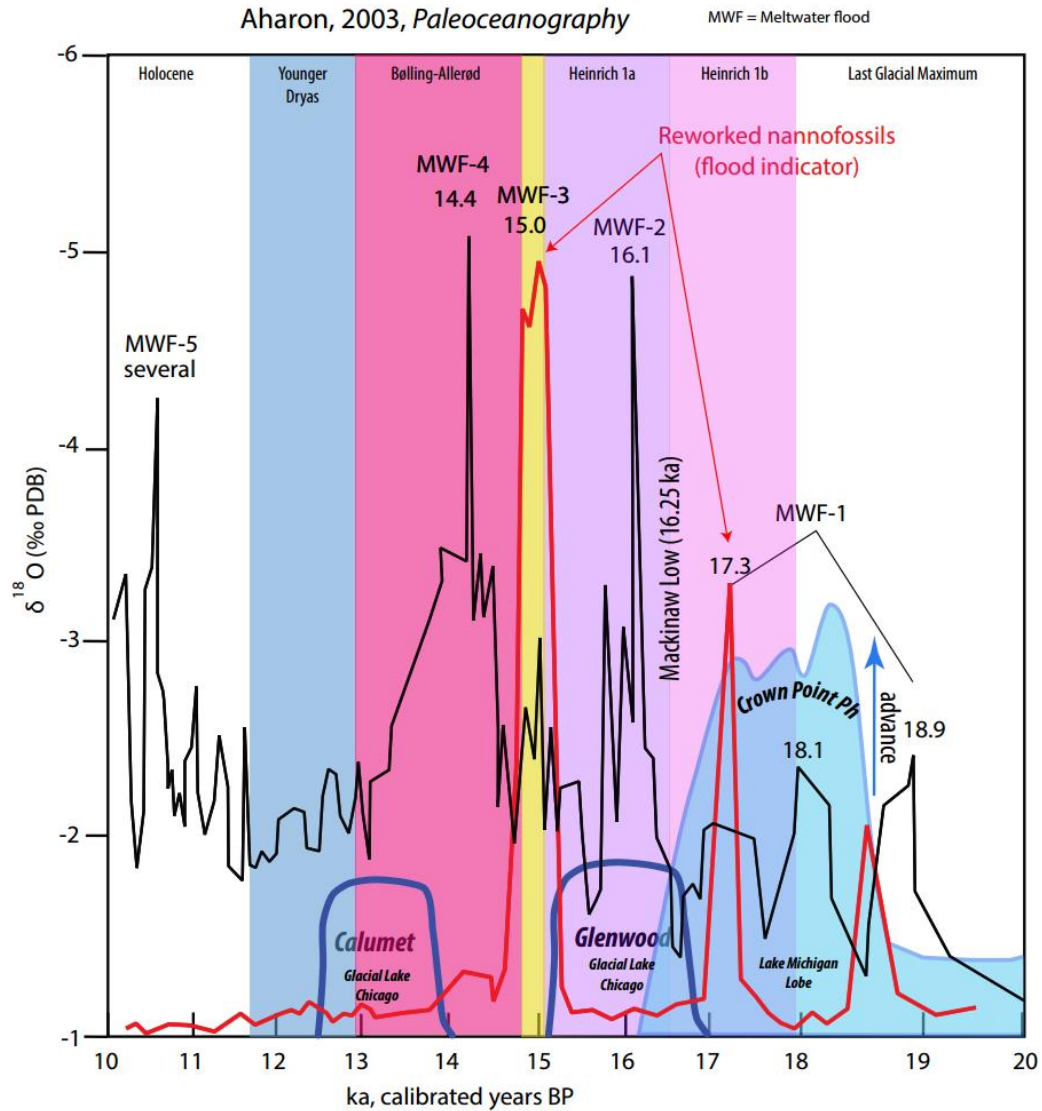


Figure 16: Comparison of Aharon's (2003) isotope curve for foraminifera, and Marchitto and Wei's reworked nannofossil concentrations, the late-stage activity (Crown Point Phase) of the Lake Michigan lobe in Illinois (Curry and Petras, 2011), and phases from the GISP2 (Andersson et al., 2003). Puzzlements include evidence for Meltwater Flood 2 (MWF-2) at about the same time of the Mackinaw low (Monaghan and Hansel, 1990) suggesting a different meltwater source and routing.

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## APPENDIX A: CORE DESCRIPTIONS

### A.1: Riggle Pond

<u>Depth (m)</u>	<u>Description</u>
------------------	--------------------

4.40-4.65	Peat, fibrous, gradually becomes less fibrous/peaty and more silty until 4.65m, color change from very dark brown (10YR 2/2) to dark brown (10YR 3/3) at 4.56m, uniform, large pieces of plant matter seen, not calcareous, gradual, unclear contact
4.65-4.75	Loam, very dark gray (10YR 3/1), somewhat fibrous, uniform, slightly calcareous, abrupt contact shown by color change
4.75-5.34	Silt loam, dark olive brown (2.5Y 3/3) uniform, gradual, slight color change to olive brown (2.5Y 4/3) near 5.34m, somewhat fibrous, not calcareous, abrupt contact
5.34-5.39	Silt loam, stratified with dark olive brown (2.5Y 3/3) and lighter, olive brown (2.5Y4/3) layers, <1cm thick, not calcareous
5.39-5.40	Core loss
5.40-5.80	Sandy loam, dark grayish brown (2.5Y 4/2), uniform, ~.5cm sand layer at 5.54 and 5.74, material becomes gradually less sandy, gradual & not clear contact, slightly calcareous
5.80-6.08	Silt, dark grayish brown (2.5Y 4/2), uniform, slightly calcareous
6.08- 6.40	Core loss
6.40-6.75	Silt, gray (10YR 5/1), vaguely laminated, somewhat calcareous (slow, but long reaction), clear lower boundary, small section (~1/2 cm thick, 2cm wide) of brown organic material at 6'40m, sparse spots of organic material throughout. Outer ~1cm of core is oxidized to 10YR 6/2 (light brownish gray), rind continues throughout core
6.75-6.90	Silt loam, stratified with dark olive brown (2.5Y 3/3) and lighter, olive brown (2.5Y4/3) layers, <1cm thick, not calcareous, clear lower contact
6.90-7.10	Silt, gray (10YR 5/1), laminated (~.2cm thick laminations), somewhat calcareous, very dark gray organic material throughout, clear lower contact
7.10-7.38	Silt, gray (10YR 5/1), bioturbated (rounded burrows, ~.8cm), burrows are a light brownish gray (10 YR 6/2) and is proximal to organic looking material that is very dark gray (10YR 3/1), somewhat calcareous

7.38- 7.40	Core loss
7.40-7.80	Silt, gray (10YR 5/1), vaguely laminated, clear lower boundary. Two thin (~2 mm) layers of medium sand (250-500mm) at 7.53m and 7.69 m. Outer ~1cm of core is oxidized to 10YR 6/2 (light brownish gray), not calcareous, clear contact
7.80-7.97	Silt, gray (10 YR 5/1), bioturbated, rounded burrows about 1-2 cm in diameter, light brownish gray (10 YR 6/2), clear contact
7.97-8.10	Silt, gray (10 YR 5/1), uniform, oxidized rind as above, not calcareous, clear contact
8.10-8.36	Silt, gray (10 YR 5/1), bioturbated (rounded burrows <1cm in diameter), root traces, not calcareous, clear contact
8.36-8.38	Loam with sand, sand is medium-grained as observed in 7.40-7.80m), gray (10 YR 5/1), uniform, not calcareous
838- 840	Core loss
8.40-8.53	Silt loam, dark gray (2.5 Y 5/1), uniform. ~1cm layers of woody organics at ~8.50m not calcareous, clear contact
8.53-8.88	Silt, gray (2.5Y5/1) thin (~.1cm) layers of black organic material, noncalcareous, disturbed lower contact
8.88-9.09	Sand, medium (~250-500mm), light olive brown (2.5 Y 5/3), common dark organic splotches with visible plant fragments, disturbed, clear lower boundary. Silty material similar to above occurs as a 1 to 5 mm thick rind, probably due to mechanical disturbance
9.09-9.29	Sand, medium (~250-500mm), olive brown (2.5Y 4/3), well sorted, uniform, calcareous. Sections of black organic material at 9.12-9.19 and 9.25-9.28. Uncommon deoxidation observed as local orange yellowish stains
9.29-9.40	Core loss

A.2: Plum Creek

PC1: Latitude/Longitude: 41.490658, -87.534400

<u>Depth (m)</u>	<u>Description</u>
0.0-0.27	Silty loam, black (10YR 2/2), structureless, no fossils seen (modern wood is visible), not calcareous, clear lower contact
0.27-0.35	Sandy loam, structureless, brown (10YR 5/3), no fossils, not calcareous, clear lower contact
0.35-0.47	Silty clay loam, dark grayish brown (2.5Y 4/2), structureless, some dark flecks seen (organics), some orange deoxidized spots (~<.5cm), rootlets seen, not calcareous, unclear lower contact
0.47-0.56	Silty clay loam with sand, dark grayish brown (2.5Y 4/2), structureless, some dark flecks seen (organics), some orange deoxidized spots (~<.5cm), rootlets seen, calcareous, unclear lower contact
0.56-1.2	Core loss
1.2-1.5	Sand and gravel, dark olive brown (2.5y 3/3), massive, gravel pieces 0.5cm-3cm, some wood pieces seen, rootlets seen, calcareous, clear lower contact
1.5-2.0	Silty loam, grayish brown (2.5Y 5/2), massive, dark gray streaks (many concentrated at 5.65ft), dropstones (small, <.5cm) throughout, calcareous
2.0-2.4	Core loss
2.4-3.4	Silty loam, gray (2.5Y 5/1), structureless, small (<.5cm) gravel pieces throughout, calcareous
3.4-3.38	Silt loam, stratified with dark olive brown (2.5Y 3/3) and lighter, olive brown (2.5Y4/3) layers, <1cm thick, not calcareous
3.38-3.66	Core loss

PC2: Latitude/Longitude: 41.490666, -87.534216

<u>Depth (m)</u>	<u>Description</u>
0.0-0.18	Loam, black (2.5Y 2.5/1), structureless, modern roots seen, not calcareous, light (not dense), clear lower contact
0.18-0.3	Silty loam, black (2.5 Y 0/1, darker than 1/1), darker than above unit, structureless, no fossils, not calcareous, clear lower contact
0.3-0.69	Peat, somewhat fibrous, black, (10YR 2/1), wood pieces throughout, color lightens to dark brown (10YR 3/3) at ~2ft, not calcareous, no lower contact seen
0.69-1.2	Core loss
1.2-2.24	Peat, very dark gray (2.5Y 3/1), some sections light olive brown (2.5 5/6), very woody, wood pieces up to 4cm long, slightly less woody at 6.1ft, structureless, not calcareous
2.24-2.44	Core loss
2.44-2.83	Peat, very dark gray (2.5Y 3/1), some sections light olive brown (2.5 5/6), very woody, wood pieces up to 4cm long, color change at 8.3ft to dark grayish brown (2.5Y 4/2), not calcareous, clear lower contact
2.83-3.19	Silty clay, gray (2.5Y 5/1), dark gray/black streaks at 9.9-10.2, calcareous, clear lower contact
3.19-3.23	Silt, gray (2.5Y 5/1), some parts deoxidized to orange, calcareous, structureless, no lower contact
3.23-3.66	Core loss
3.66-3.9	Silty clay with sand/gravel, dark gray (2.5Y 4/1), also black and orange (deoxidized) parts, interlayered but structureless, calcareous, clear lower contact
3.9-4.39	Silty loam, gray (2.5Y 5/1), structureless, some dark gray streaks, dropstones (small, <.5cm), some deoxidized areas, calcareous
4.39-4.88	Core loss

PC3: Latitude/Longitude: 41.490006, -87.534084

<u>Depth (m)</u>	<u>Description</u>
0.0-0.3	Silty loam, black (10YR 2/1), some wood fragments, structureless, not calcareous, clear lower contact
0.3-0.35	Sand, medium, grayish brown (2.5Y 5/2), small (<1cm) gravel pieces, clear lower contact
0.35-0.61	Silty clay, grayish brown (2.5Y 5/2), small (<1cm) dropstones throughout, strutureless, not calcareous
0.61-1.2	Core loss

PC4: Latitude/Longitude: 41.490666, -87.534216

<u>Depth (m)</u>	<u>Description</u>
0.0-0.24	Silty loam, black (2.5Y 2.5/1), large wood fragments, massive, not calcareous, clear lower contact
0.24-0.34	Peat, black (5Y2.5/1), darker than above unit, not dense, wood fragments throughout, not calcareous
0.34-1.2	Core loss
1.2-1.43	Peat, black (5Y2.5/1), darker than above unit, not dense, wood fragments throughout, not calcareous, large wood fragments (up to ~1.25cm), clear lower contact
1.43-1.9	Peat, very dark brown (10YR 2/2), wood fragments throughout, large wood fragments at 6.25, structureless, not calcareous, clear lower contact
1.9-2.16	Peaty loam, black (5Y2.5/1), color changed to dark grayish brown from 6.9-7.0ft, not dense, no fossils seen
2.16-2.4	Core loss
2.4-2.6	Peaty loam, black (5Y2.5/1), color changed to dark grayish brown from 6.9-7.0ft, not dense, wood fragments seen, clear lower contact

2.6-2.87	Silt loam, very dark gray (10YR 3/1), structureless, no fossils seen, not calcareous, clear lower contact
2.87-3.19	Silty clay, light brownish gray (10YR 6/2), structureless, no fossils seen, calcareous, 2.86-2.9m darker-- grayish brown (10YR 4/2)
3.19-3.66	Core loss
3.66-4.48	Silty clay, light gray (10YR 7/1), structureless, sandy section at 13.0-13.1, small rock fragments throughout, some dark streaks, structureless, calcareous
4.48-4.88	Core loss

PC5: Latitude/Longitude: 41.493075, -87.541679

<u>Depth (m)</u>	<u>Description</u>
0.0-0.26	Silt loam, very dark gray (2.5Y 3/1), some wood fragments, structureless, (modern soil?), not calcareous, clear lower contact
0.26-0.41	Silt loam, black (2.5Y 2.5/1), no fossils, structureless, not calcareous, abrupt lower contact
0.41-0.7	Sandy silt, grayish brown (2.5Y 5/2), some part deoxidized to orange, some areas black, structureless, not calcareous, no lower contact
0.7-1.2	Core loss
1.2-1.72	Sandy silt, olive brown (2.5Y 5/2), some part deoxidized to orange, some areas black, structureless, calcareous, abrupt lower contact
1.72-1.89	Silty clay, gray (5Y5/1), dark streaks, some sandy sections, structureless, calcareous, abrupt contact
1.89-1.9	Large wood piece
1.9-2.05	Silty sand, very dark gray (5Y 3/1), [colors vary, some orange sections, some black, some lighter gray, somewhat stratified with color, calcareous, no fossils visible
2.05-2.4	Core loss
2.4-2.7	Sand, fine-medium, dark gray (10YR 4/1), also orange/black deoxidize

areas, silty clay layer at 8.7ft, structureless, no fossils, calcareous, abrupt contact

- |          |   |
|----------|---|
| 2.7-2.8  | Silt and gravel, dark gray (2.5Y 4/1), gravel pieces up to .5 inch, structureless, calcareous, abrupt lower contact |
| 2.8-3.1  | Silty clay, dark gray (2.5Y 4/1), some small gravel pieces (~.5cm), structureless, calcareous, no fossils visible   |
| 3.1-3.66 | Core loss   |



## APPENDIX B: DATED MATERIAL

B.1: Riggle Pond, dated material pictures

NB: One side of the square in each picture is 1 cm in length



Figure 17: ISGS-A3468; Depth: 455-460 cm; Material: Needles, wood fragments

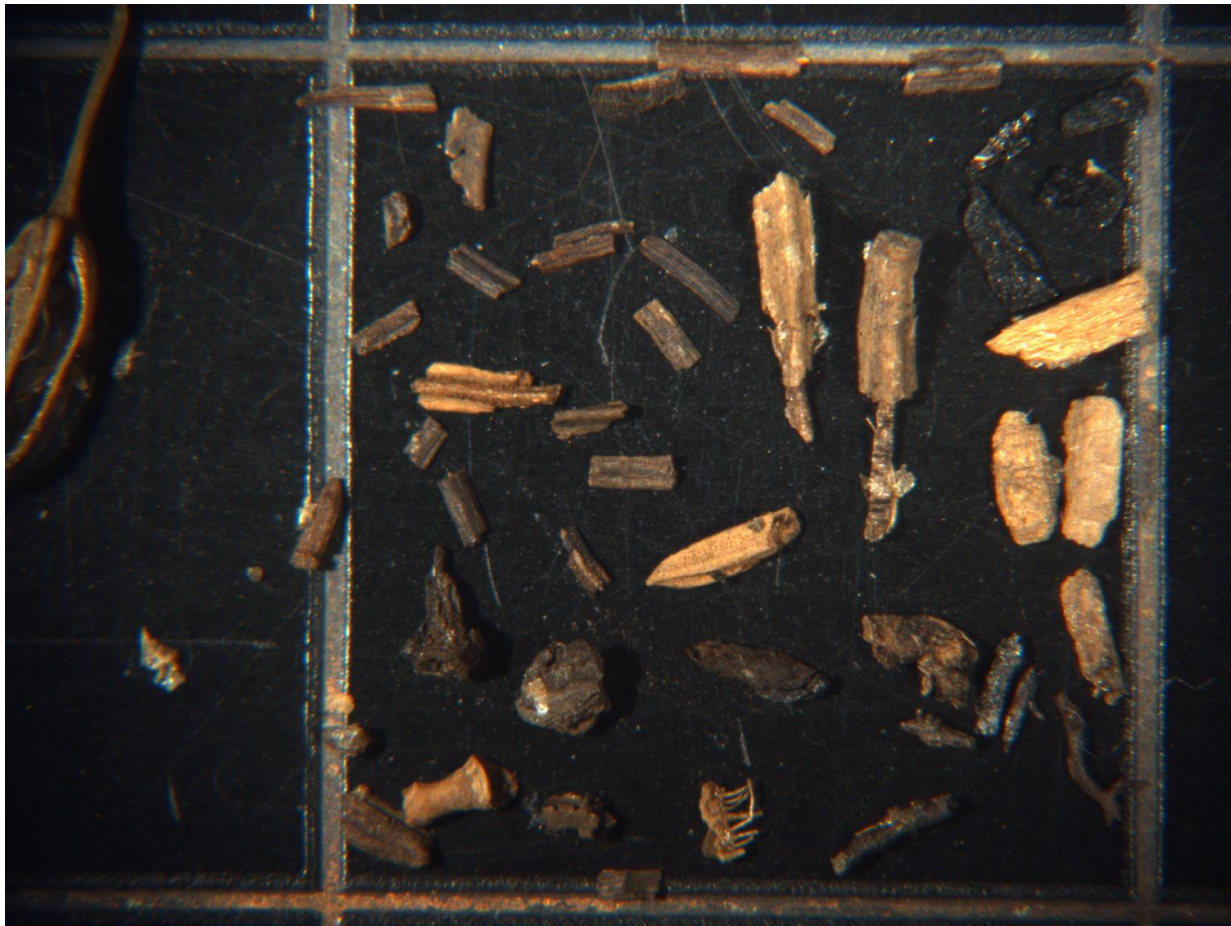


Figure 18: ISGS-A3383; Depth: 460-465 cm; Material: Needles, wood fragments

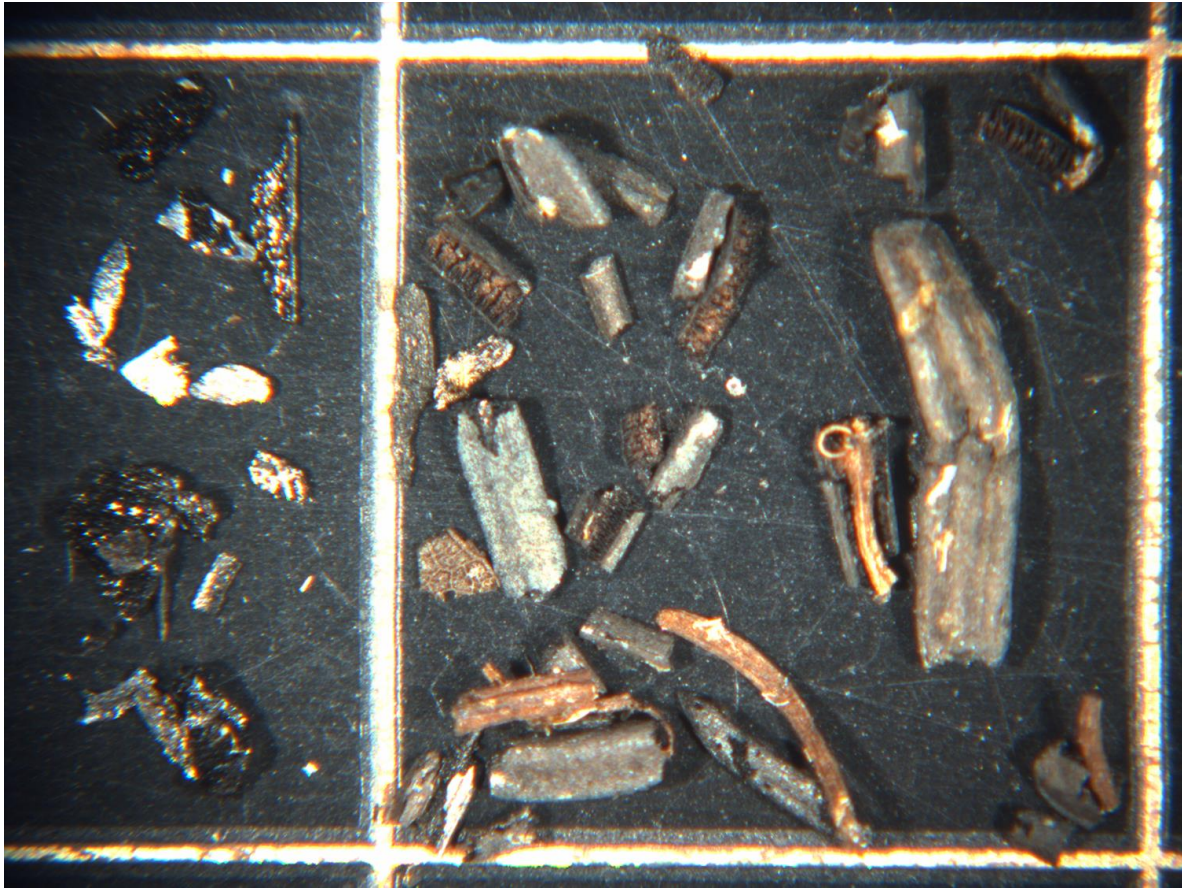


Figure 19: ISGS-A3385; Depth: 534-539 cm; Material: Needles, wood, charcoal



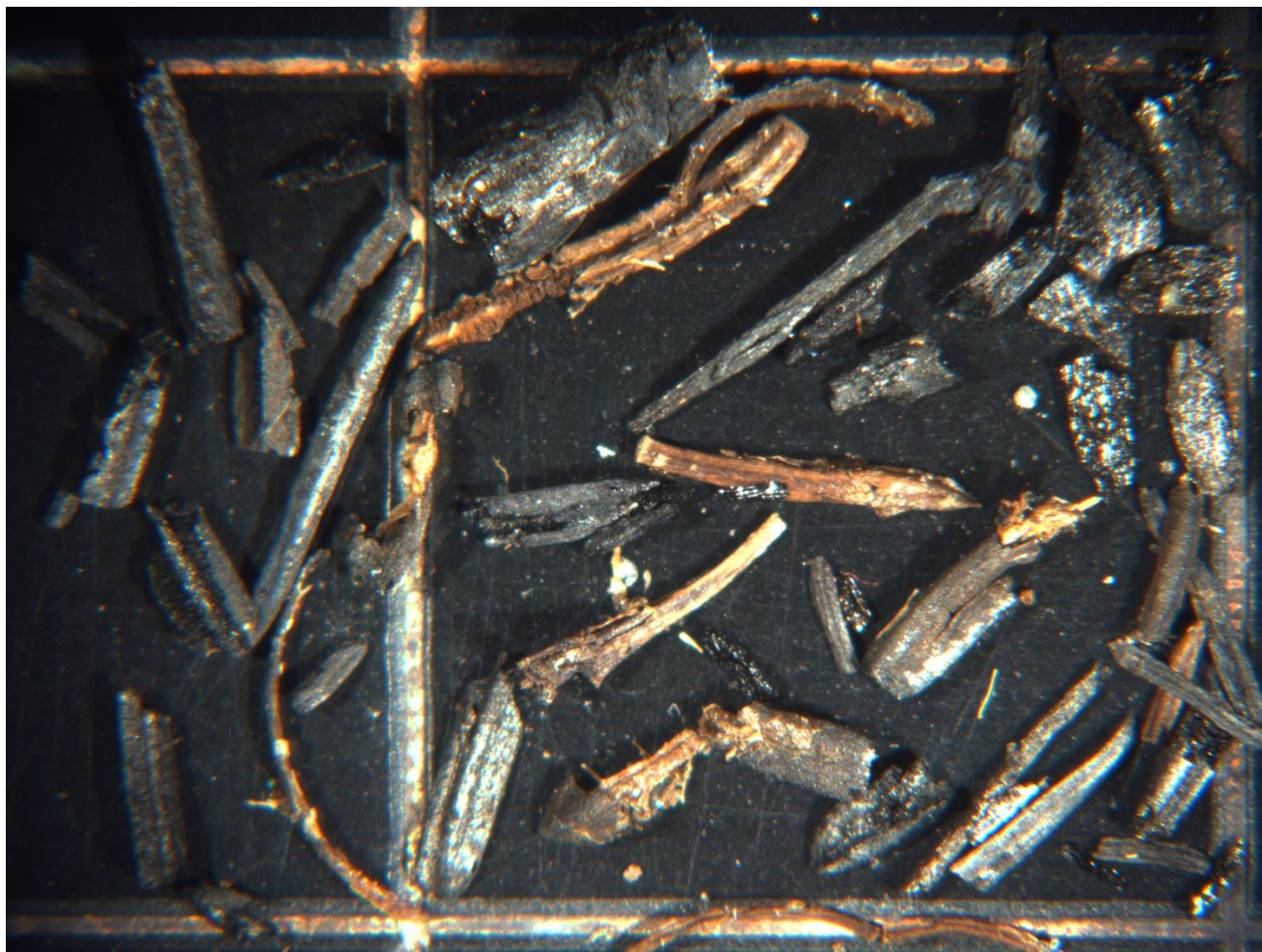


Figure 20: ISGS-A3384; Depth: 535-540 cm; Material: Wood fragments, plant macro fossils

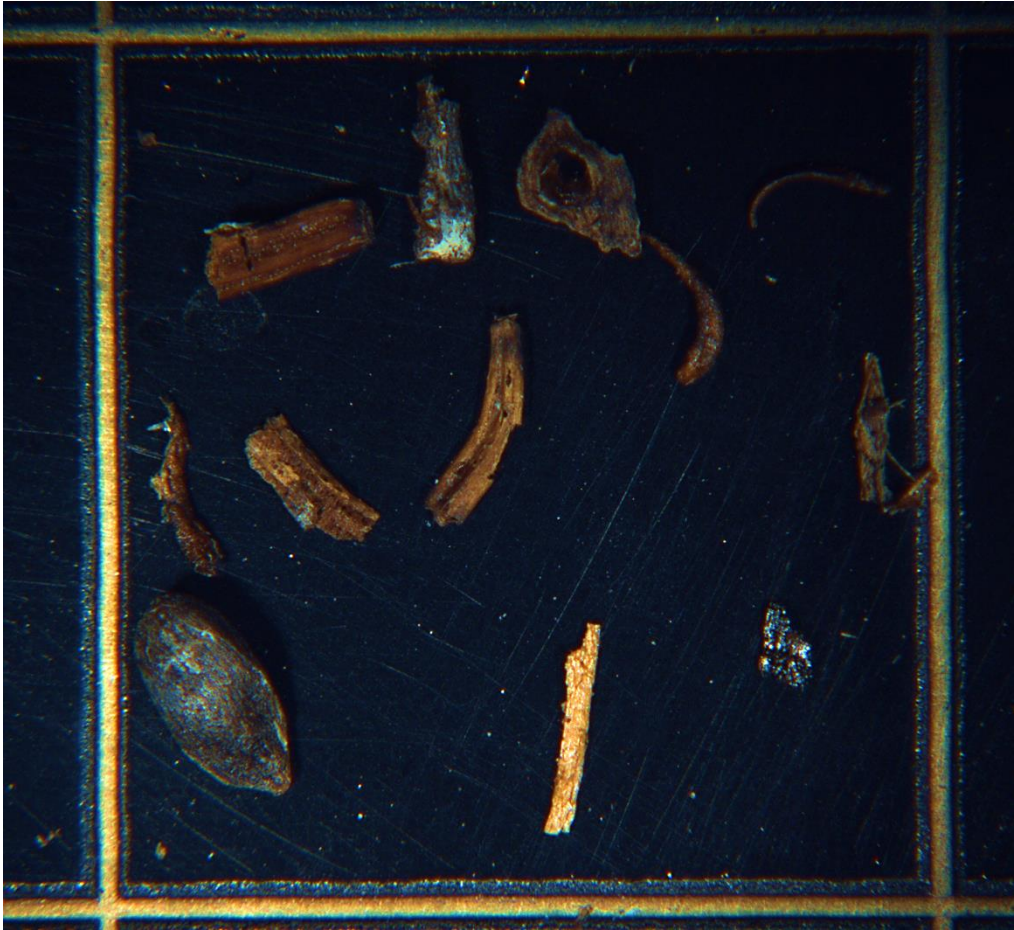


Figure 21: ISGS-A3466; Depth: 853-858cm, corrected to 594; Material: Needles, plant macrofossils; Note the smaller relative mass of material picked compared to other samples



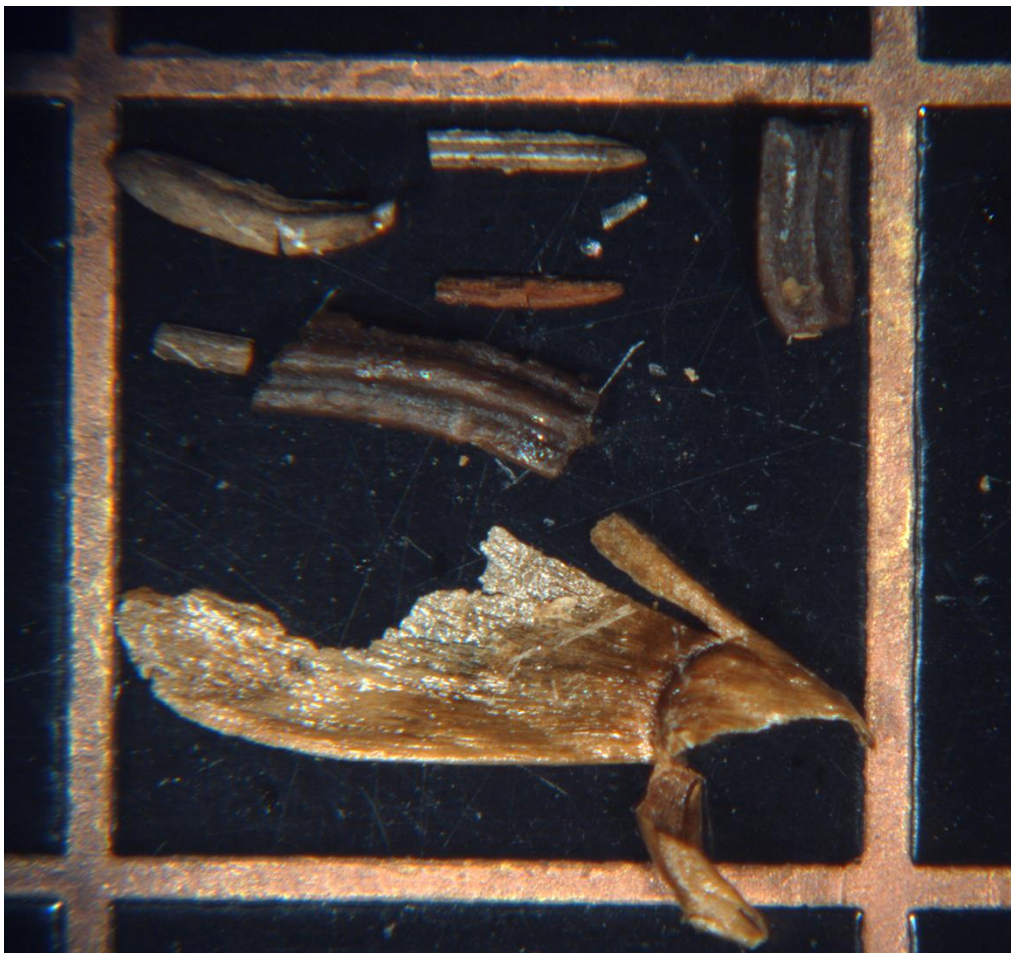


Figure 22, ISGS-A3467; Depth: 640-655 cm; Material: Needles, plant macrofossils

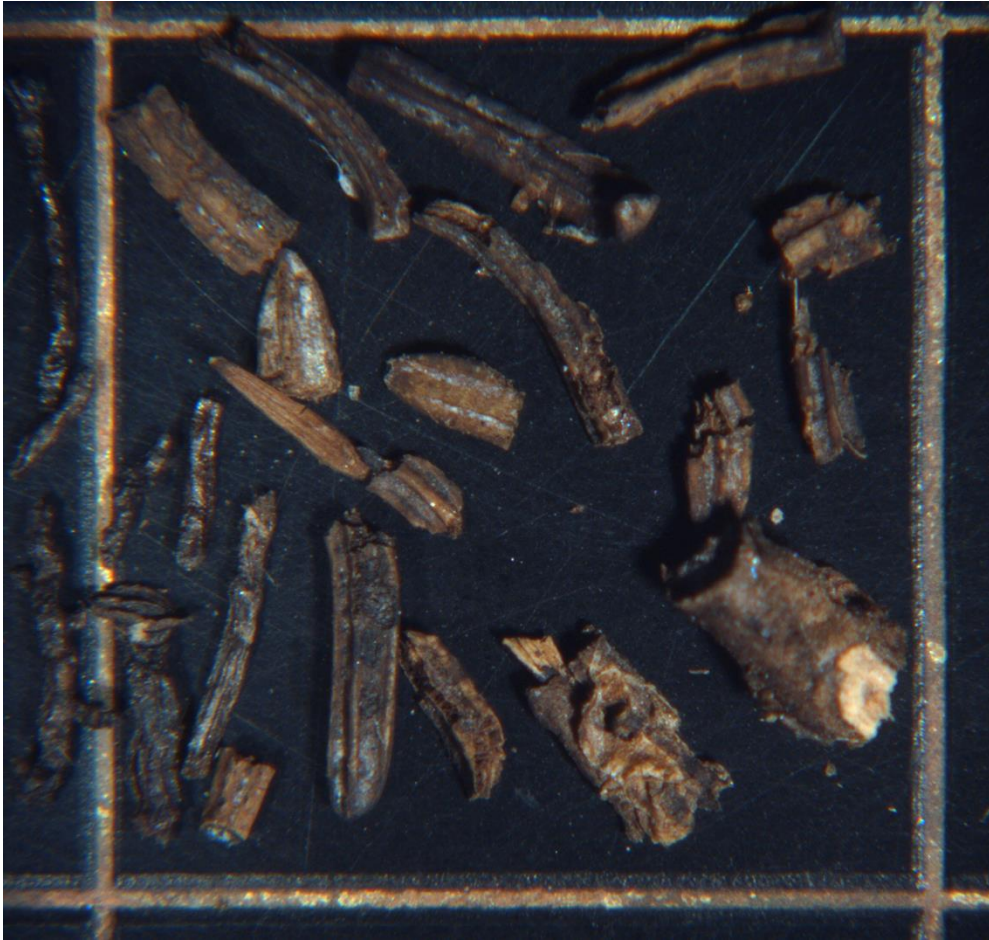


Figure 23: ISGS- A3465; Depth: 700-710 cm; Material: Needles, wood fragments



Figure 24: ISGS-A3335; Depth: 909-924 cm; Material: Needles



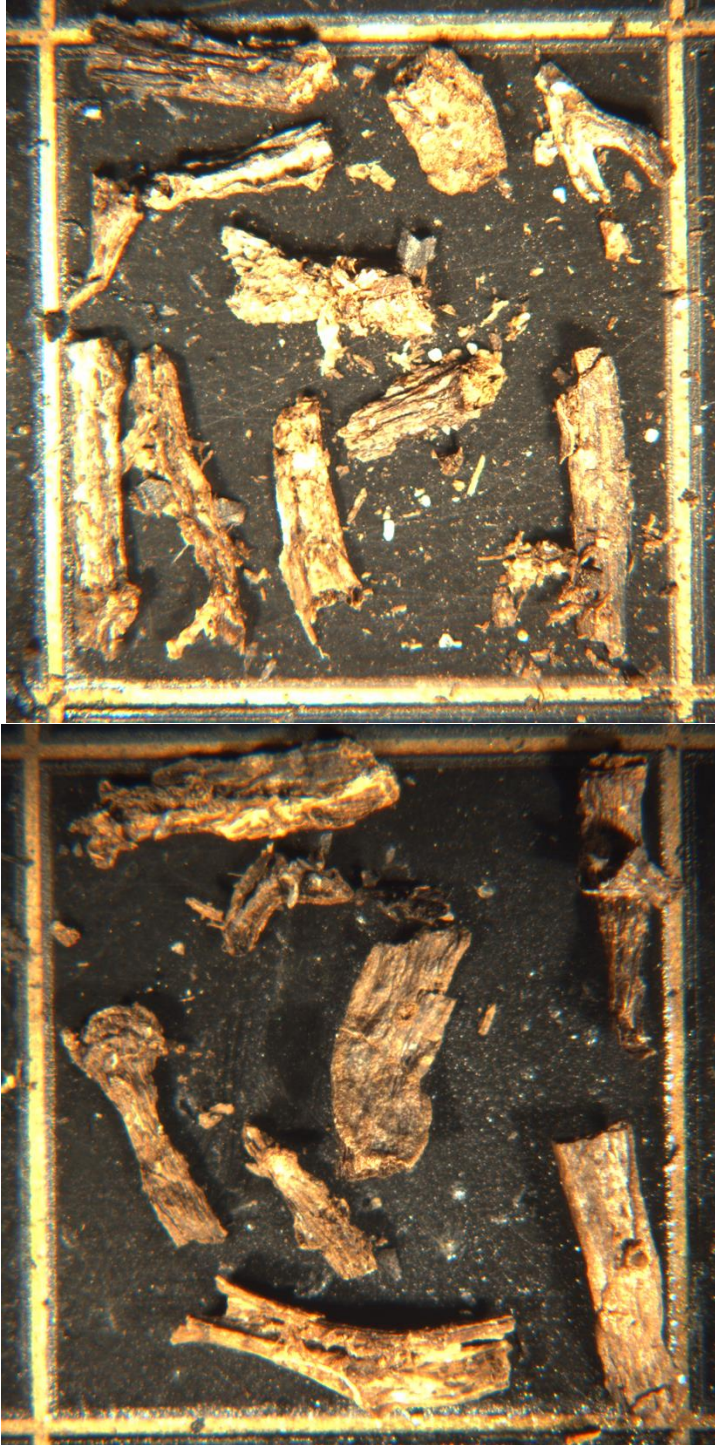


Figure 25: ISGS-A3334; Depth: 909-924 cm; Material: Woo

B:3

Table 2: Summary table of Glenwood Radiocarbon dates

Boring label	Lab ID Number	Depth (cm)	Material	14C age	Error +/-	Author	Calibrated age	Sigma 1 range		Elevation (m)
N/A	IU-62	N/A	Wood	12400	300	Schneider and Reshkin, 1970	14650	15204	14096	N/A
N/A	W-140	N/A	Wood	12650	350	Rubin and Suess, 1955	15117	15847	14389	N/A
N/A	W-161	N/A	Wood	12220	350	Rubin and Suess, 1955	14452	15039	13865	N/A
N/A	ISGS-1190	N/A	Wood	12660	140	Hansel et al., 1985b	15024	15386	14661	N/A
N/A	ISGS-1332	N/A	Wood	12770	180	Hansel et al., 1985b	15242	16705	14779	N/A
N/A	ISGS-1418	N/A	Wood	12500	210	Hansel et al., 1985b	14762	15222	14302	N/A
N/A	ISGS-1549	N/A	Spruce cones	13870	170	Liu, 1987	16795	17064	16525	N/A
N/A	ISGS-1570	N/A	Driftwood	14100	640	Liu, 1987	16825	17031	16623	N/A
RP	ISGS-A3468	457	Wood fragments	11545	30	This study	13385	13429	13342	189.88
RP	ISGS-A3383	467	Wood fragments	11745	35	This study	13545	13581	13484	189.78
RP	ISGS-A3385	537	Charcoal	12015	35	This study	13778	13923	13778	189.08

Boring label	Lab ID Number	Depth (cm)	Material	14C age	Error +/-	Author	Cal age	Sig up	Sig down	Elevation (m)
RP	ISGS-A3384	537	Plant macros	12160	30	This study	14050	14105	13997	189.08
RP	ISGS-A3466	594 *corrected from 855*	Wood, needles	12705	35	This study	15145	15216	15080	188.51
RP	ISGS-A3467	650	Wood fragments	12915	35	This study	15420	15517	15307	187.95
RP	ISGS-A3465	705	Needles, wood	13275	35	This study	15960	16050	15870	187.4
RP	ISGS-A3335	917	Needles	13260	60	This study	15942	16048	15833	185.28
RP	ISGS-A3334	917	Wood fragments	13450	50	This study	16184	16273	16093	185.28
Bretz outcrop	ISGS-A7087	n/a	Wood	13700	80	This study	16535	16671	16358	194.15
PC2	ISGS-A3541	372	Needles	14075	50	This study	17110	17217	17004	189.96
PC2	ISGS-A3543	378	Needles	14085	50	This study	17130	17225	17021	189.90
PC2	ISGS-A3542	384	Needles	14115	50	This study	17180	17282	17061	189.84

Table 2 continued

Boring label	Lab ID Number	Depth (cm)	Material	14C age	Error +/-	Author	Cal age	Sig up	Sig down	Elevation (m)
PC4	ISGS-A3544	287	Needles	13790	45	This study	16680	16808	16544	190.78
PC4	ISGS-A3545	308	Needles	14140	50	This study	17210	17319	17099	190.63
PC4	ISGS-A3546	405	Needles	14050	50	This study	17080	17282	17061	189.66
PC5	ISGS-A3692	131	Wood fragment s	13395	50	This study	16120	16210	16030	189.77
PC5	ISGS-A3693	137	Needles	13105	45	This study	15730	15830	15630	189.71
PC5	ISGS-A3547	170	Needles	13150	45	This study	15800	15894	15703	189.38
PC5	ISGS-A3548	203	Needles	13675	45	This study	16490	16591	16362	189.05
DYER2	ISGS-A3549	n/a	Needles	13065	45	This study	15665	15782	15568	194.15
DYER2	ISGS-A3550	n/a	Needles	13355	50	This study	16070	16170	15976	194.15

Table 2 continued

## APPENDIX C: ADDITIONAL INFORMATION REGARDING METHODS

C.1: Grain size  
SOP used for all grain size analysis

Sample identification	
Sample identifiers	Sample Name : PC

Particle Type	
Non-spherical particle mode	Yes
Is Fraunhofer type	No

Material properties	
Material name	Silica (RI 1.544, AI 0.0)
Refractive index	1.544
Absorption index	0.000
Particle density	1.00 g/cm <sup>3</sup>
Different optical properties in blue light	No

Dispersant properties	
Dispersant name	Water
Refractive index	1.330
Level sensor threshold	100.000

Measurement duration	
Background measurement duration (red)	60.00 s
Sample measurement duration (red)	90.00 s
Perform blue light measurement?	No
Assess light background stability	No

Measurement sequence	
Aliquots	1
Automatic number of measurements	No
Number of measurements	5
Delay between measurements	90.00 s
Pre-measurement delay	30.00 s

Measurement obscuration settings	
Auto start measurement	No
Obscuration low limit	0.10 %
Obscuration high limit	20.00 %
Enable obscuration filtering	No

Accessory control settings	
Accessory name	Hydro MV
Is accessory dry?	No
Stirrer speed	3400 rpm
Ultrasound percentage	20 %
Manual tank fill?	No
Degas after tank and cell fill	Yes
Sonicate to stability?	No
Ultrasound mode	Continuous (From Sample Addition)

Clean sequence settings	
Clean sequence type	Normal
Sonicate during clean?	No

Analysis settings	
Analysis model	General Purpose
Single result mode	No
Number of killed inner detectors	0
Blue light detectors killed	No
Fine powder mode	No
Analysis sensitivity	Normal
Analysed as Mastersizer 3000E?	No

Result Settings	
Result range is limited	No
Result Units	Volume
Extend Result	No
Result Emulation	No

User sizes for histograms and tables	
Use user sizes	No

Data export output	
Enabled?	Yes



Orientation	Row
File format	Tab-separated
Include header row?	Yes
Format?	Yes
Overwrite?	Append
Parameters	Record Number,Sample Name,Measurement Date Time,Dx (10),Dx (50),Dx (90),Operator Name,Instrument Serial No.,Result In Sizes
Filename	File Name.txt

Averaging	
Averaging enabled?	No

Printing options	
Printing enabled?	No